# Linford Low Energy Houses

Other

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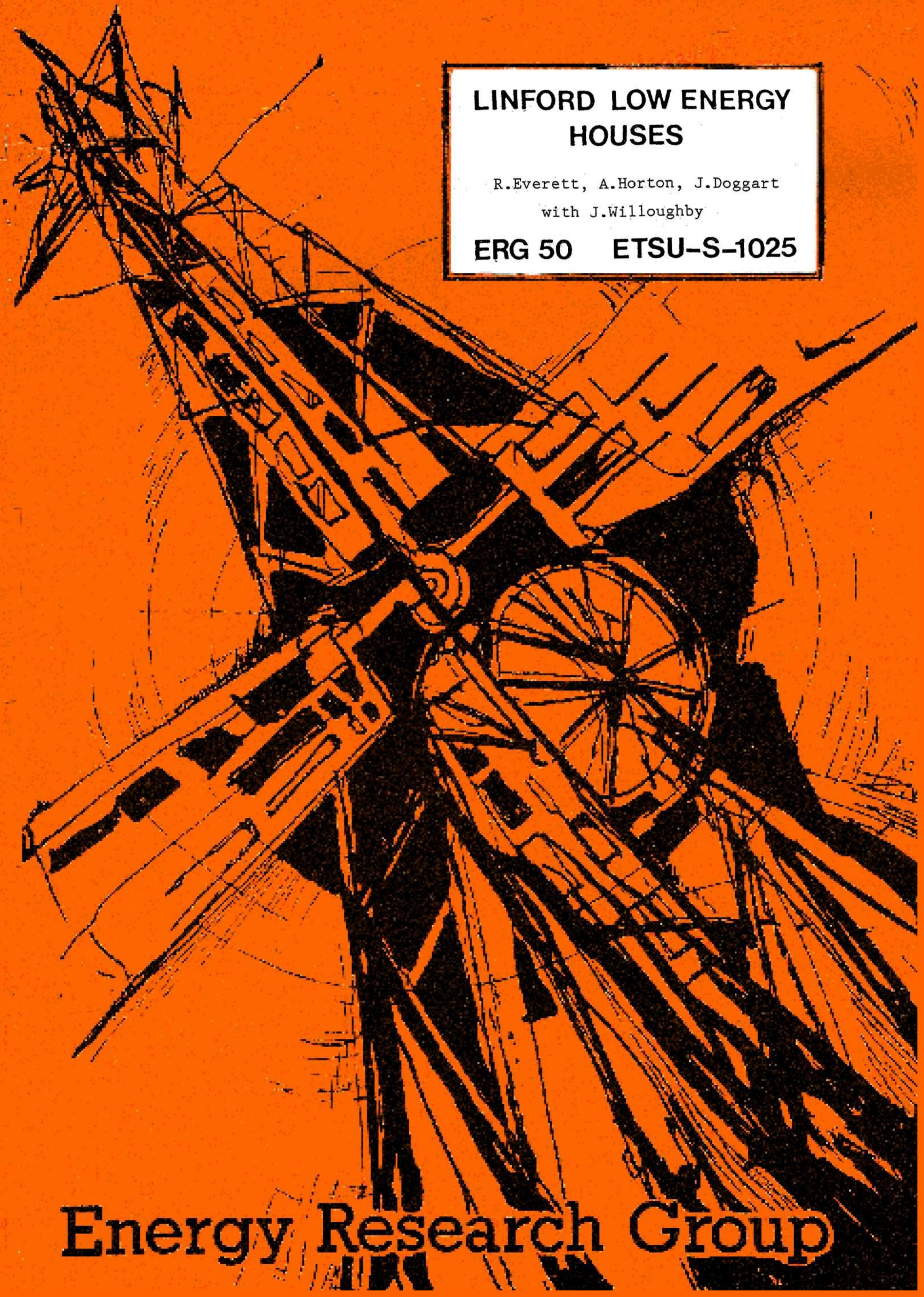
R.Everett, A.Horton, J.Doggart
with J.Willoughby

**ERG 50 ETSU-S-1025**



Energy Research Group

# LINFORD LOW ENERGY HOUSES

R.Everett, A.Horton, J.Doggart
with J.Willoughby

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*This is the final report on the performance of 8 low-energy, passive solar houses at Great Linford, Milton Keynes, monitored by the Open University Energy Research Group (ERG), for the Milton Keynes Development Corporation (MKDC), under contract to the Energy Technology Support Unit (ETSU) at Harwell.*

*The principal authors are R. Everett and A. Horton (ERG), and J. Doggart (MKDC). Editorial support was provided by J. Willoughby (ETSU).*



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# CONTENTS

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# 1. THE LINFORD PROJECT

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This chapter is intended to give the reader an overview of what was involved in the Linford project. At the same time the contents and structure of this report are outlined.

# 1. THE LINFORD PROJECT

## 1.1. Introduction

The Linford Project involved designing, building and monitoring eight low energy passive solar houses. The houses were built on the south edge of the Linford Gridsquare in Milton Keynes (Figure 1.1) by the developers, S and S of Woburn Sands.

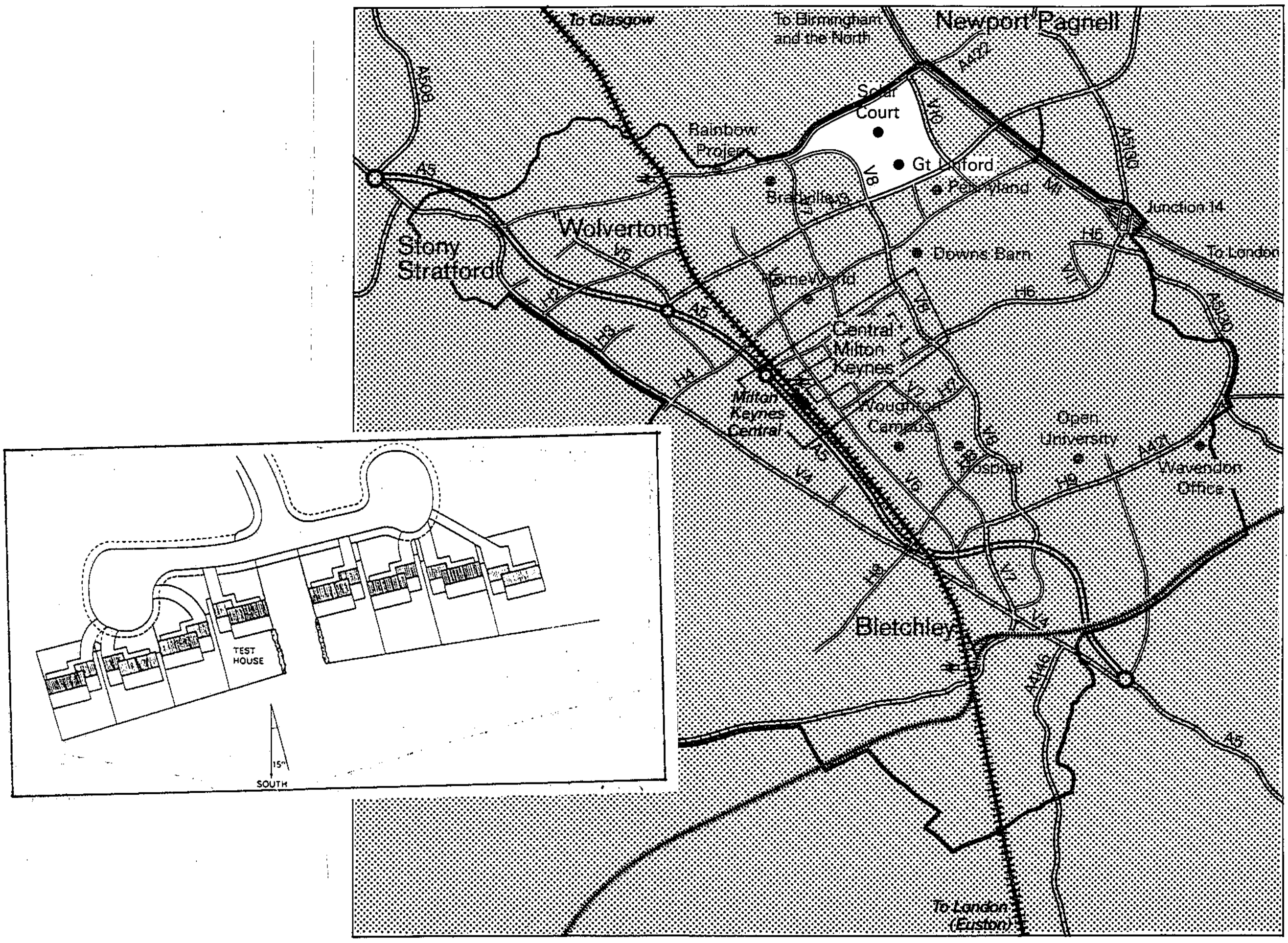


Figure 1.1 Location of the Linford houses

## 1.2. Design and Construction

The project started in 1976 (Figure 1.2) when there was very little U.K. experience of low energy house design. The first two or three years of the project were, therefore, taken up with design evaluation, planning and computer modelling. This initial work (discussed in more detail in Chapter 2) generated house designs for two estates: Linford and Pennyland.

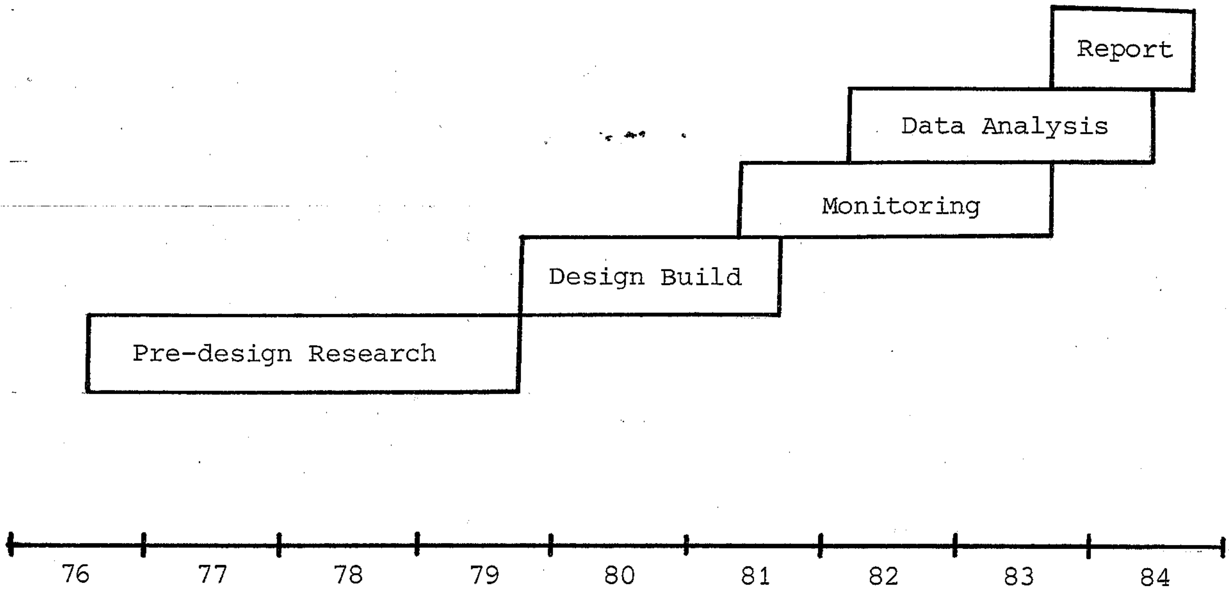


Figure 1.2 The Time Scale of the Linford Project

The eight houses at Linford were monitored intensively in order to be able to evaluate their performance accurately. In the Pennyland project more than 200 houses were monitored at a lower level to assess the 'real' effect of four different levels of insulation and varying degrees of passive solar design. The two projects were seen as being complementary.

The Linford houses (Figure 1.3) were built in 1980/81. They are detached, south-facing houses, built approximately to current Danish insulation requirements. The glazing has been concentrated on the south side with only small windows on the north facade. Their design and construction is described in more detail in Chapter 3.

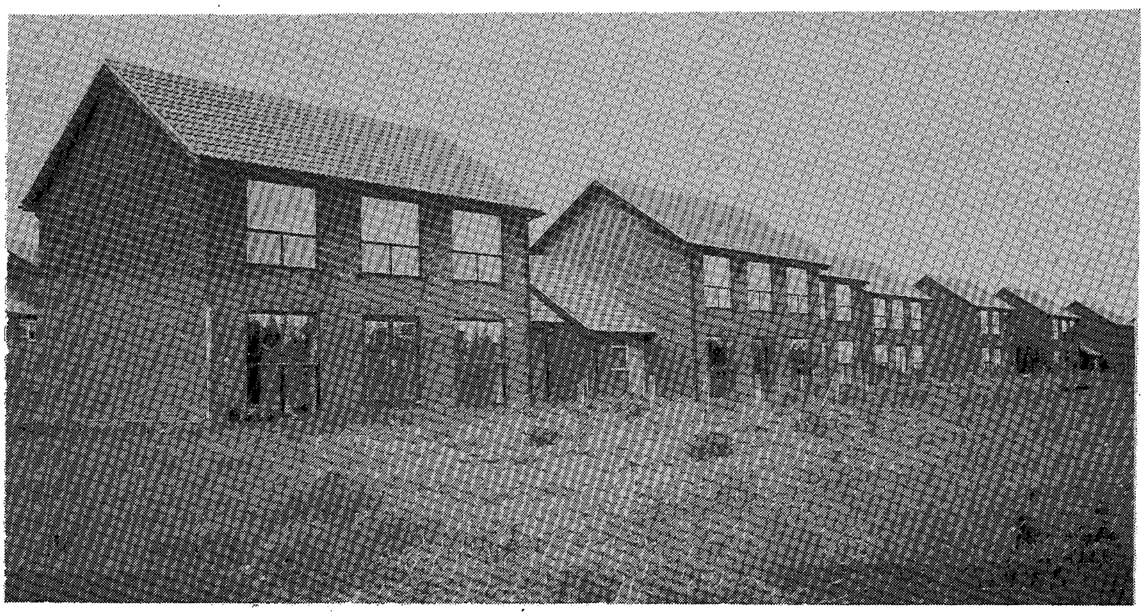

Figure 1.3 The Linford houses

During the building phase the Building Research Establishment observed the construction process to monitor the ease of construction and any potential problems of building highly insulated houses. These results are summarised in Chapter 4 along with a discussion of the experience gained from designing and building these houses. A later thermographic survey (see Chapter 8) was also found useful in assessing the quality of the construction.

## 1.3. Monitoring

One of the eight houses was designated an unoccupied test house. Detailed experiments were conducted in this house which could then be compared with the 'real' data obtained from the seven occupied houses. A weather station was erected in the test house garden to provide data for both the Linford and Pennyland projects. During an eighteen-month period monitoring equipment was installed in the houses both during and after the construction period. This operation took much longer than expected as detailed in Chapter 16.

The monitoring was fairly intensive with about 30 sensors being installed in each house. Temperatures, delivered and useful energy consumptions and window openings were recorded in the occupied houses; in addition heat flux and air infiltration measurements were taken in the test house.

The output from the various sensors was recorded on magnetic tape by four data loggers situated in the garage of the test house (Figure 1.4).

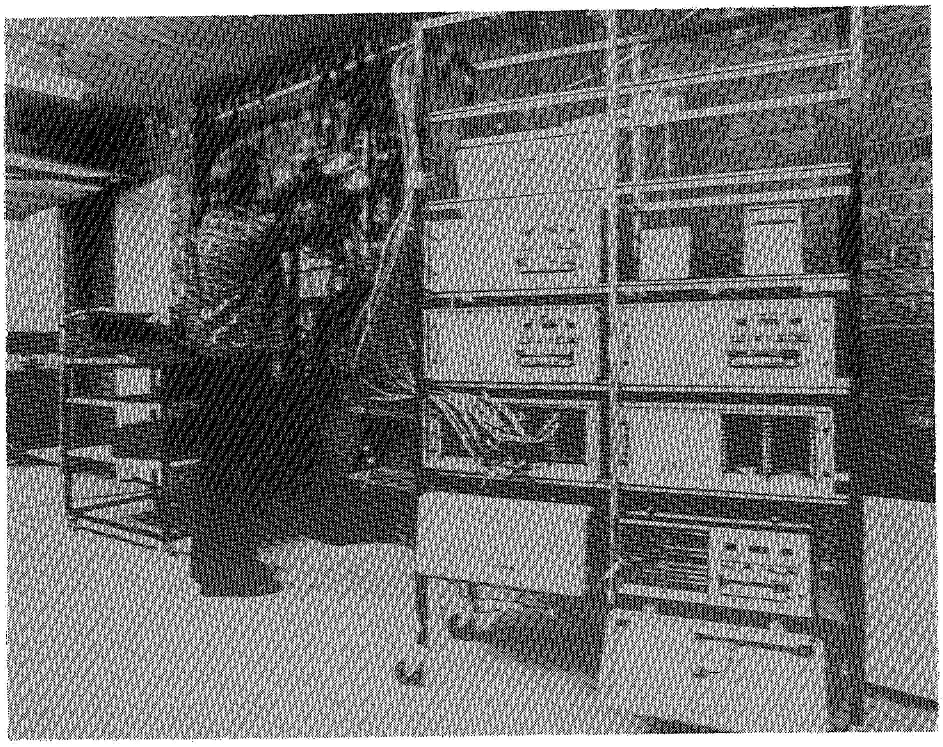

Figure 1.4 The data logger installation

Data from the magnetic tapes was then fed directly into an Open University main frame computer. The next major activity involved 'cleaning' the data, i.e. removing recording errors, which again took longer than expected. This was mainly due to the enormous amount of data generated by the experiment which amounted to about 40 megabytes of information. Put another way, if it was to be printed out on A4 (both sides) at a standard 10 characters/inch, it would require a roll of paper 25 kilometres long and would weigh half a ton. If burnt, in a suitable stove, it would provide the heating needs of a typical Linford house for 6 months.

A major part of the experiment has been to devise data base systems to manipulate this vast amount of data. This is discussed in Chapter 16.

## 1.4. Data Analysis

Another novel aspect of this project was the development of statistical methods to evaluate the thermal characteristics of the houses and the effective solar aperture. This involved the use of regression analysis to establish fabric heat losses (Chapter 8) and the detailed estimates of solar gains shown in Chapter 10.

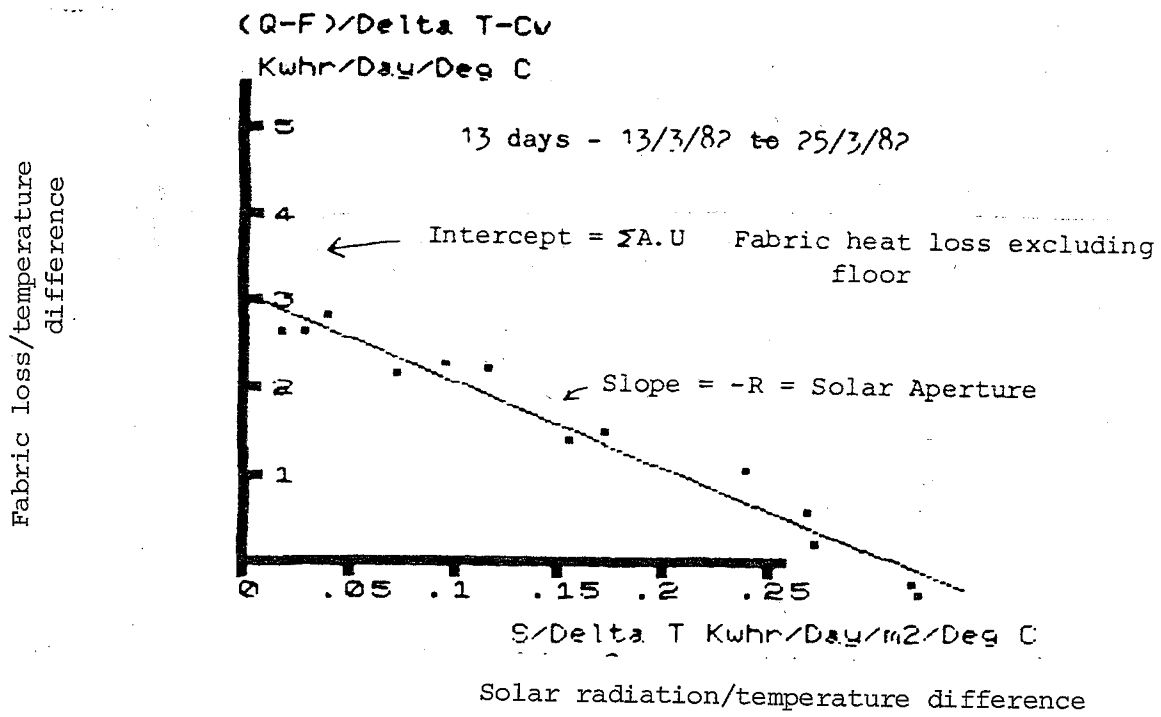


Figure 1.5 A typical example of the regression analysis used to estimate solar aperture and fabric heat losses

The fabric heat losses have also been studied in the test house using heat flux meters built specifically for this purpose at the Open University (see Chapter 16 for the details of the sensors and Chapter 8 for information on the measurement results).

The measurement of infiltration in the test house both by British Gas and the Open University has generated an invaluable source of data on infiltration rates under various conditions of wind speed and direction and temperature difference (Chapter 9). Using these measurements it has been possible to produce empirical relationships between these variables. Together with measurements of window opening this has been extremely useful in estimating infiltration and ventilation rates in the occupied houses.

Measurements in the test house, together with information from the weather station, have been used to estimate the extent of the physical heat transfers - heat losses from the warm interior via the fabric elements and infiltration, and heat gains from solar radiation. As can be seen from Figure 1.6 the measurements from the occupied houses were needed to complete the picture. These gave details of room temperatures (Chapter 14), incidental gains (Chapter 11), window openings and the efficiency of the heating systems (Chapter 13).

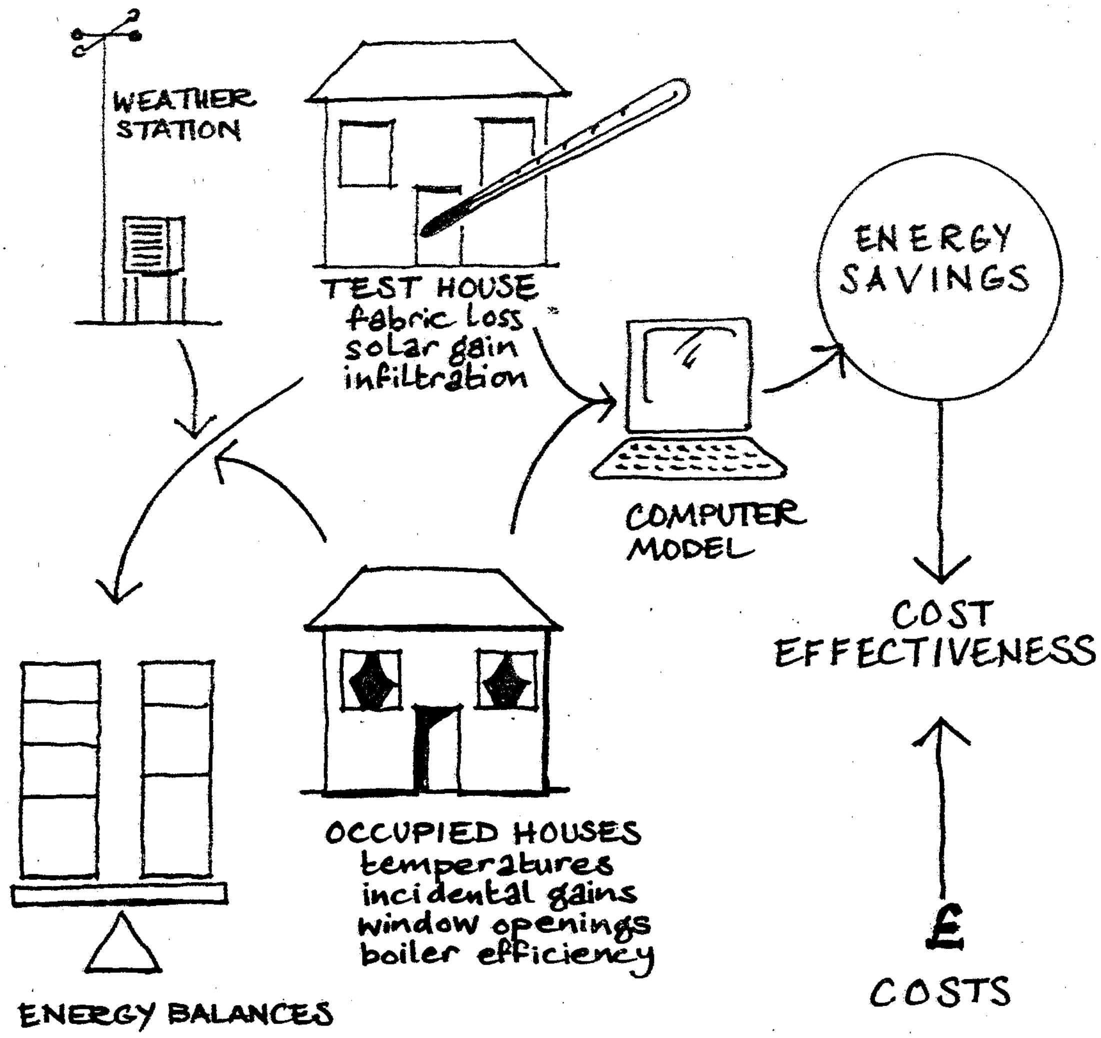


Figure 1.6 The relationship between measurements in the test house and the occupied houses

The basic information on energy consumption and use is given in Chapter 5. Here the considerable effect of temperature on energy consumption is demonstrated and the variation in the costs of providing energy for heating, hot water, cooking and electrical appliances is shown. More details about comfort conditions, given in Chapter 14, show not only how occupancy choice varies but also how the internal temperatures vary over time and with outdoor conditions. The graphical output from the computer has proved an invaluable aid for examining this sort of data, as shown in Figure 1.7.

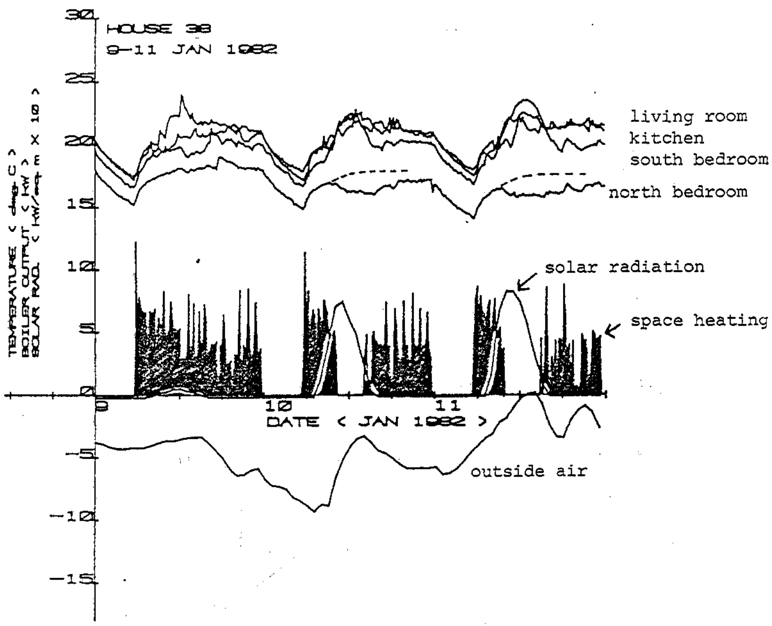


Figure 1.7 A typical graphical output, showing the effect of solar radiation on space heating consumption and temperature

The information from the test house and occupied houses has been used to create an energy balance for a selection of the occupied houses. This shows the balance of heat losses and gains as can be seen in Figure 1.8. Details of the energy balances are to be found in Chapter 12.

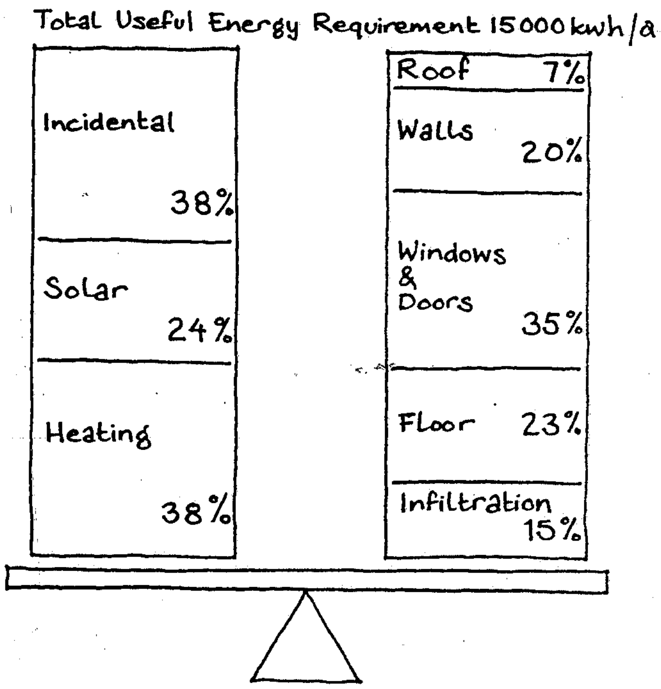


Figure 1.8 A typical energy balance

## 1.5. Energy Savings and Costs

In the Pennyland project the energy consumption of groups of houses of varying thermal performance was compared. The energy savings could be found from this comparison. However in the Linford project there were no 'normal' houses with which to compare energy consumptions. Therefore computer modelling was used to estimate the energy saving potential of the various measures. The energy savings are set out in Chapter 6.

Whether the energy savings are worthwhile depends on the cost of the measure. A firm of quantity surveyors produced a cost breakdown for the Linford houses as-built and 'normal' Linford houses, with insulation levels to current U.K. Building Regulations and glazing evenly distributed rather than concentrated on the south facade. The extra costs of each of the energy saving measures was then compared with the cost of the energy saved to give an idea of the cost effectiveness or payback time. All the measures proved to be economically attractive as is shown in Chapter 7.

## 1.6. Conclusion

The complexity of the Linford Project can be seen from the flow diagram in Figure 1.9. It can be seen as a cycle starting with an initial body of preconceived notions and assumptions coupled with an initial set of results from computer modelling. From these results came an energy brief which influenced the design and construction of the houses. At the same time a monitoring process began with the selection and installation of measuring instruments and finished with an enormous computer data base.

The data analysis improved the physical theory and advanced the preconceived notions. A revised model gave more realistic estimates of thermal performance and energy consumption. This allowed improved estimates of energy savings and, with cost information, cost effectiveness.

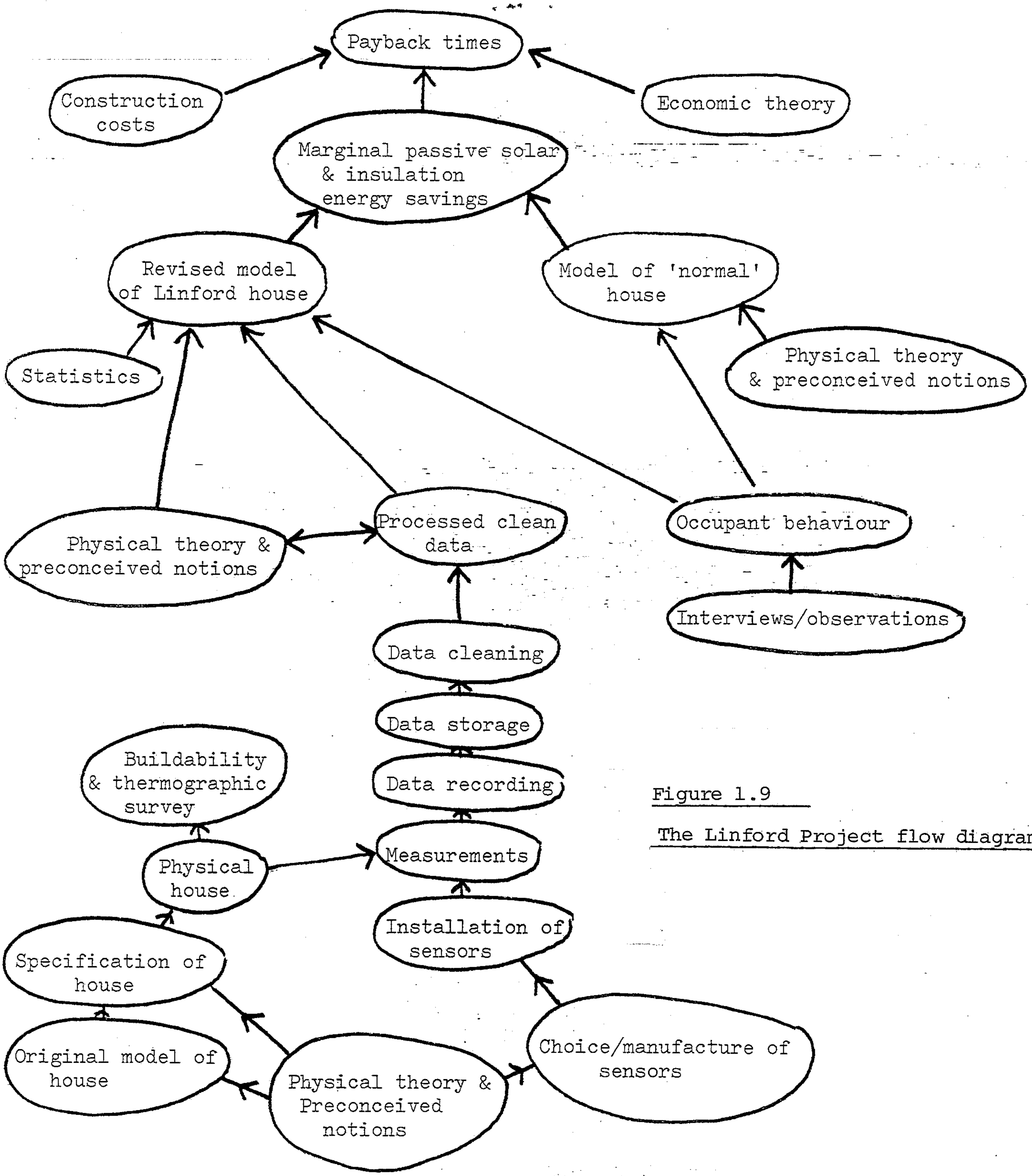


Figure 1.9

The Linford Project flow diagram

# 2. DESIGN BACKGROUND

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This chapter traces the origins of the project back to 1976 and early interests in cost-effective low energy passive solar houses in the UK. Thus the chapter summarises previous work on active solar heating and subsequent research into passive solar house design which culminated with an energy brief for the Linford houses.

## 2. DESIGN BACKGROUND

The Linford project and the companion Pennyland field trial both have common origins that date back before the Arab oil embargo of 1973, an event that brought rapid changes in thermal building regulations in countries such as Denmark and Sweden and a renewed interest in solar energy in France and the U.S.A.

At that time very little of Milton Keynes or the Open University actually existed, almost all of the area being farmland.

The original city plan for Milton Keynes was drawn up at the end of the 1960's in an era of low fuel prices. Energy considerations did not enter into the design. A possible scheme for a city layout centred on public transport and a district heating main was rejected in favour of the current low density 'Los Angeles' layout, which makes car ownership essential and makes any future combined heat and power retrofit rather difficult.

Energy projections being produced in the early 1970's indicated that by the time Milton Keynes was scheduled to be finished, in the 1990's, there could be a U.K. energy shortage. The inhabitants could thus expect to enter the 21st Century faced with large heating bills and expensive and scarce fuels for transport.

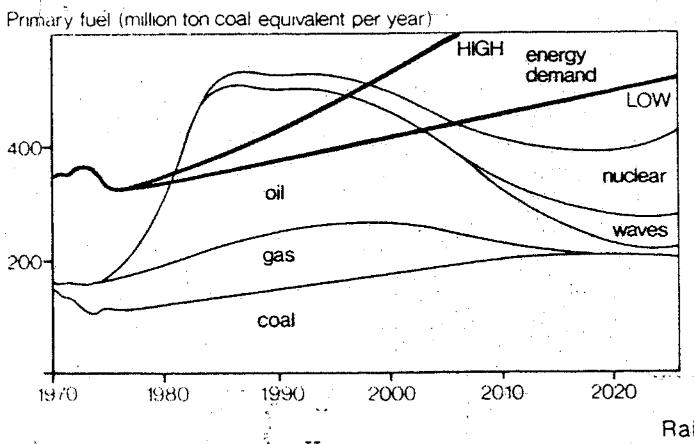



Figure 2.1. A 1976 U.K. Energy Scenario (ref.2.1.)

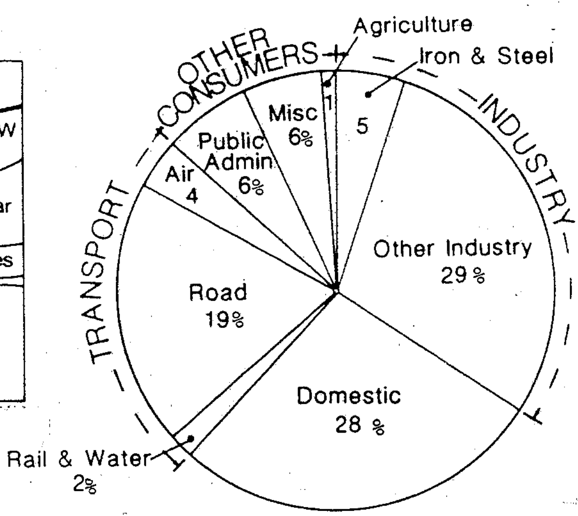


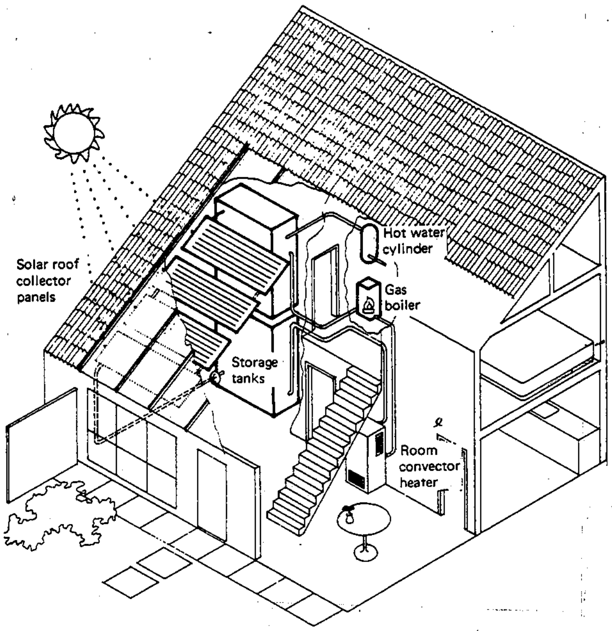

Figure 2.2. 1981 U.K. End Use Energy Consumptions (ref.2.2)

At the time it was realised that nearly 30% of U.K. energy consumption was used in heating houses (see figure 2.2). The construction of a new city of 200,000 inhabitants obviously was a golden opportunity to demonstrate various energy saving measures, not only for the benefit of the inhabitants, but also to influence energy conservation in the rest of the U.K.

## 2.1 The Bradville Solar House

The interest in low energy houses in Milton Keynes began in 1972, when Dr. Steven Szokolay of the Polytechnic of Central London suggested the construction of an active solar house. He approached Milton Keynes Development Corporation with a scheme using 40 $m^2$ of solar panels which he estimated could provide 60% of a house heating energy requirements.

A special system was designed to adapt a standard M.K.D.C. rented house and in 1974 this was installed in a house on the Bradville estate in the north of Milton Keynes. Monitoring was started by the Built Environment Research Group (B.E.R.G.) of the P.C.L. and involved the current authors to a considerable extent.



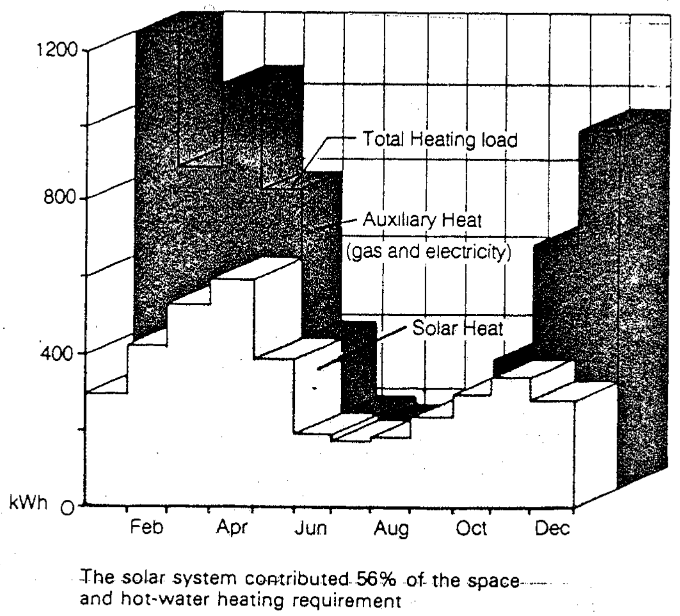




Figure 2.3 Bradville Solar House

Figure 2.4 Solar Energy Use at the Solar House, 1979/80

The system took advantage of the large south-facing pitched roof of the house, tilted at 30° to the horizontal. The panels were set in the roof and water passing through the collectors fed a storage tank running the whole height of the house. This hot water was then used to preheat domestic hot water and provide some space heating.

Performance, especially in space heating, was slightly disappointing initially, but after modifications were made to the panel absorptivity, convector heater design and frost protection system, the design performance was largely reached. In the year 1979/80, the system provided 56% of the total heating needs of the house, 71% of the water heating requirement and 47% of the space heating load. Full details may be found in the final monitoring report (ref. 2.3).

By 1976, it was already clear that even if the Bradville house reached its design performance, the high cost of the system would lead to payback times of the order of 50 years. More reasonable solutions were clearly needed.

## 2.2 Cost-effective Energy Conservation

In 1976 concern about the Energy Crisis was at its peak and it was time to design a more cost-effective low energy house with a shorter payback time of 10-15 years.

At this time Milton Keynes Development Corporation set up a liason group with the newly founded Energy Research Group of the Open University to consider energy problems. This Energy Consultative Unit consisted of M.K.D.C. architect John Doggart and Professor Peter 'Jake' Chapman, director of E.R.G. It also drew on the expertise of other members of the research group as well as the Built Environment Research Group at the P.C.L. This arrangement was instrumental in starting many energy conservation projects. The diversity of these is described in the final report of the Energy Consultative Unit 'Energy Projects in Milton Keynes', published in 1982 (ref.2.4).

Much material on Scandinavian insulation methods and on U.S. passive solar designs was gathered by E.R.G. member Colin Moorcraft (ref.2.5). It was felt that a very economical low energy house could be designed using the best of Scandinavian insulation practice, active solar heating drawing on the lessons from the Bradville solar house, and passive solar design.

The aim of a design with a payback time of 10-15 years would be compatible both with mortgage finance considerations from a home-buyer's point of view and, more important, with the Treasury Test Discount Rate criterion used for investment in energy generation, power stations, searching for oil and gas, etc.

The insistence on cost-effectiveness was endorsed by the potential funding bodies, the Department of the Environment and the Department of Energy. This was especially true for the large scale Pennyland project where the extra costs of insulating almost 200 houses were considerable.

Although a lot was known about the suggested energy saving measures from a qualitative point of view, not much was known quantitatively, making it very difficult to assess performance and payback times. Thus for both the Linford and Pennyland projects it was necessary to embark on a detailed study of the potential costs and benefits of these measures.

The main areas where quantitative knowledge was lacking were:-

Active solar heating

Although it was clear that the Bradville design as built would not be cost-effective, it was not known whether the costs could be reduced. There was no hard published data on even the performance of small solar water heaters.

Passive solar heating

Buildings such as the St. George's School extension in Wallasey, Cheshire (Reference 2.6) showed great promise for passive solar design in the U.K. Although the building clearly worked, it was not clear <u>why</u> it worked, whether it was due to the solar gains, the high insulation level, or the very low ventilation rates used.

There was no information on the effects of variations in house orientation, overshading, glazing type and window area on house energy consumption.

Insulation

In 1976, the U.K. Building Regulations had been improved to require 50 mm of loft insulation and a wall U-value of 1.0 $W/m^2\ ^oC$. Double glazing was relatively rare and wall insulation to a U-value of 0.3 $W/m^2\ ^oC$ and floor edge insulation seemed almost unheard of. Neither the costs nor the performance of these novel insulation techniques seemed really known. The cost side of the cost-effectiveness equation required considerable research.

Heating system performance

There was almost no information on high efficiency heating systems for well-insulated houses. Boiler manufacturers appeared either not to know, or be unwilling to disclose, the efficiencies of their products.

Occupant behaviour

Assessing the performance of a low energy house design required some assumptions about occupant behaviour, most important internal temperatures and levels of free heat gains from cooking, lighting, etc. This basic ignorance of normal U.K. domestic energy use had led to gross overestimates of both space and water heating requirements for the Bradville solar house and consequently extremely over-optimistic estimates of the payback time of the solar heating system.

The available occupancy information was extremely sparse, mainly bacause of the lack of previous field trials. Although the Building Research Establishment had conducted extensive field trials in the period 1948-51 (Reference 2.7) they were obviously hampered in their interpretation by the lack of computers. The most useful data came from Electricity Council trials carried out in the late 60's and early 70's mainly concerned with the viability of night storage heating (References 2.8 and 2.9 ).

The Department of the Environment had started its 'Better Insulated House' monitoring programme in 1974, but little of the data had been processed by 1977.

Because of the lack of quantitative information on how passive solar designs might operate in the U.K. climate, a computer programmer, Bob Everett, was employed at the P.C.L. to set up a computer model of the proposed house designs. This model, simplified from the U.S. National Bureau of Standards model 'NBSLD' (Reference 2.10), was used to generate the solar shadow prints used for the Pennyland estate layout, evaluation of the effects of glazing area in the passive solar house design, and in conjunction with a model of the Bradville active solar heating system, used to evaluate the conflicts between active solar heating and house insulation.

Although the following description of the house design process is broken down into fairly logical steps, the actual process was one of a spiral of house design, costing, energy evaluation, new house design, more costing....

The process involved many discussions between members of MKDC, the Open University Energy Research Group, the Built Environment Research Group and the estate architects. The mix of architects, modellers and energy policy experts created considerable problems of mutual understanding and priorities.

For descriptive purposes, the design sequence has been broken down into:

1. The evaluation of possible active solar heating.
2. Insulation savings starting from a standard house design.
3. Savings due to correct orientation and avoidance of overshading in estate layout.
4. Effects of concentrating the glazing on the south side and varying its area.
5. Thermal mass, summer shading and overheating.

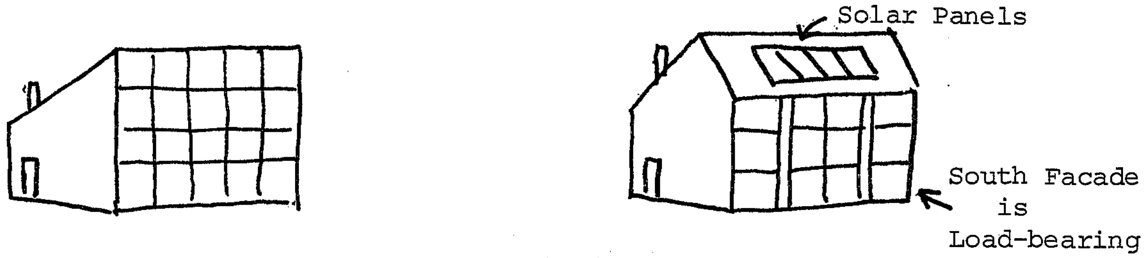
## 2.3 Low energy house design study

### 2.3.1 Economics of active solar heating

It was suggested that active solar heating should be incorporated in some of the houses, either in the form of a 30 $m^2$ water and space heating system or as a simpler 5 $m^2$ water heating only system.

Using the computer model developed at the P.C.L. to fit the Bradville house system, it was found that insulation could save space heating energy at a lower cost than active solar heating could supply it. Detailed economic analysis of a wide range of active solar systems showed that the most economic systems were the small water heating types of around 5 $m^2$ (Reference 2.11). However, even these could not be justified within the 10-15 year payback times used to justify the other measures, despite considerable research into low-cost fabrication and installation (see Reference 2.4 for a simple thermosyphon system).

Although they were never included in the final Linford houses, the design was left with a south-facing pitched roof, to allow possible installation at the house owner's discretion. This, in turn has affected the passive solar design since it has meant that the south facade of the house was load bearing creating cost implications limiting the area of south-facing glazing (see Figure 2.5).




Wallasey School Design Concept

Pennyland/Linford design concept with space for active solar panels

Figure 2.5 Original Design Ideas

2.3.2 Evaluation of the effects of insulation

The cost-effectiveness of insulation measures was done by using a simple rule of thumb derived from degree-day calculations that a reduction of 1 W/$^{o}$C in the total house heat loss of a 3-bedroom end of terrace house would save 40 kWh/yr of useful space heating energy.

Starting from the then current (1976) Building Regulation standards (essentially unfilled cavity walls, single glazing and 50 mm roof insulation) the costs and likely fuel savings of a wide range of insulation measures for new houses could be calculated. Plotting a graph of fuel saving against extra construction cost, as in Figure 2.6, gave an indication of the payback time. The steeper the slope, the shorter the payback time.

Although loft insulation was the most cost-effective measure, the thickness was restricted to 150 mm because of doubts over the condensation risk in the loft space. The total package of measures chosen for the Linford houses, 100 mm wall insulation, 150 mm roof insulation, double glazing and floor edge insulation, was estimated to have a payback time in flat rate terms of about 15 years.

Figure 2.6 is simplest to understand in flat-rate payback terms, but other financial criteria can be plotted onto it in order to compare the energy saving investment with investments in other means of producing energy. These more complex criteria tend to make the insulation savings even more economically attractive.

This insulation cost-effectiveness process is revisited in Chapter 7, with post-experiment costs, which in practice appear to be significantly less than the original estimates.

2.3.3 Avoiding overshading in estate layout

Although not a problem in the Linford houses, which are conveniently sited on the southern edge of a grid square, considerations of estate layout to minimise overshading formed a considerable part of the design study with regard to the adjacent Pennyland estate. This topic is discussed in greater detail in the report on that project and in Reference 2.12.

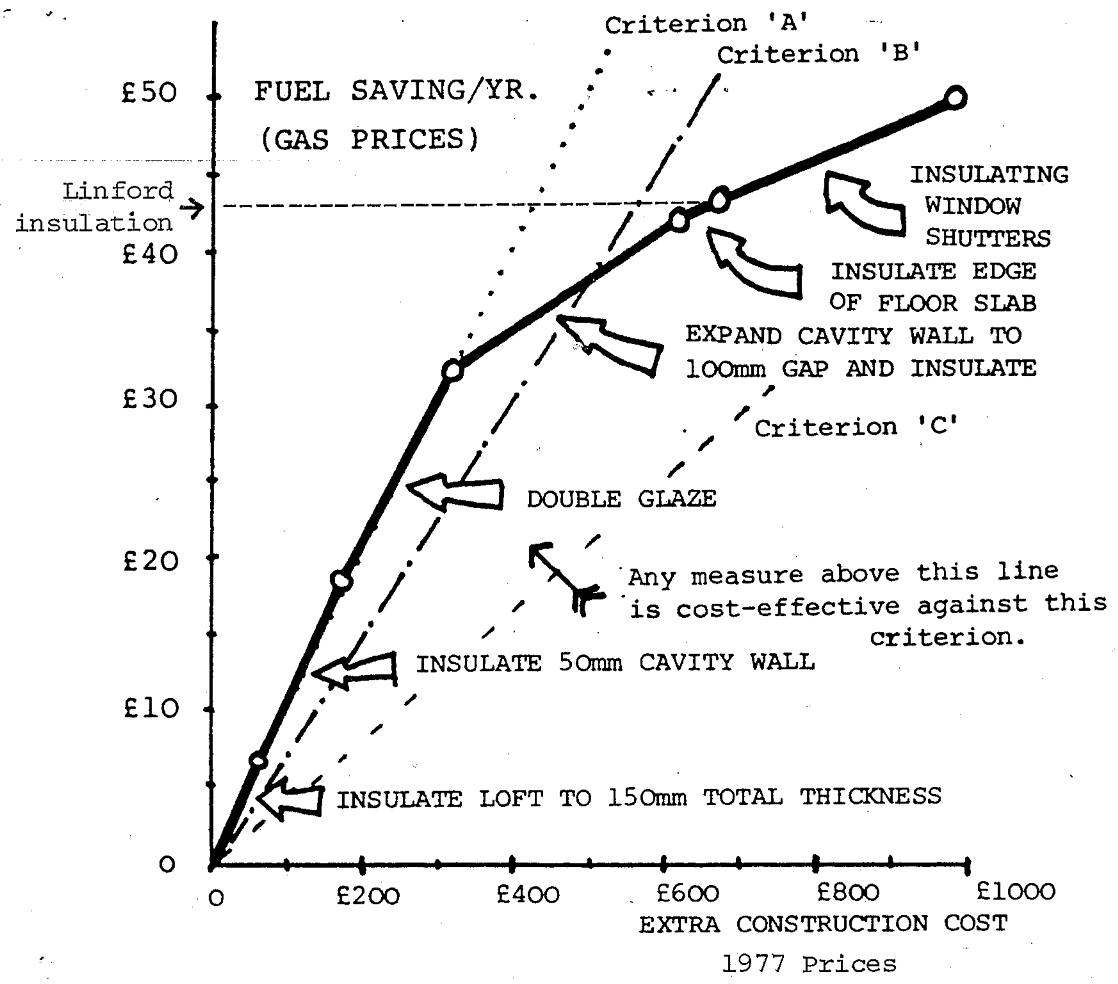



Figure 2.6 Original Design Ranking Of Insulation Measures - ref 2.12

Pennyland style house - 90 $m^2$ floor area

Financial criteria:

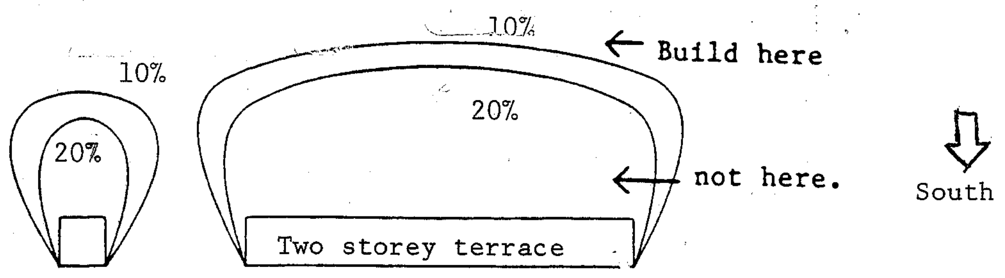
A. A nominal 'private investor's' criterion, a 10 year flat rate payback time.

B. A 'pessimistic public sector' criterion using a Net Present Cost evaluation with a discount rate of 7%, an investment lifetime of 40 years and assuming a zero real rate of fuel prices.

C. A 'realistic public sector' criterion, using a Net Present Cost evaluation with a discount rate of 7%, and investment lifetime of 40 years and a real rate or rise of fuel prices of 4% per annum.

Briefly, a set of solar shadow prints were generated using the solar routines of the NBSLD program showing the 'energy shadow' lying to north of a terrace of houses. This was calculated in terms of the percentage reduction in solar energy penetrating a south-facing double glazed window at normal ground floor height to the north of the overshading houses over a heating season. These shadow prints were then used in the laying out of the Pennyland estate, allowing quite a high density of houses in places by skillful mixing of single and two storey houses and terraces at 45° to south.

Roughly speaking the shadow prints are equivalent to a simpler criterion that the midwinter sun should just graze the roofline of one row of houses in order to penetrate the ground floor windows of the next row (see Figure 2.8).




Percentage reduction in solar radiation through south-facing window 1.2 m from ground over period November to March.

Figure 2.7 Solar shadow prints

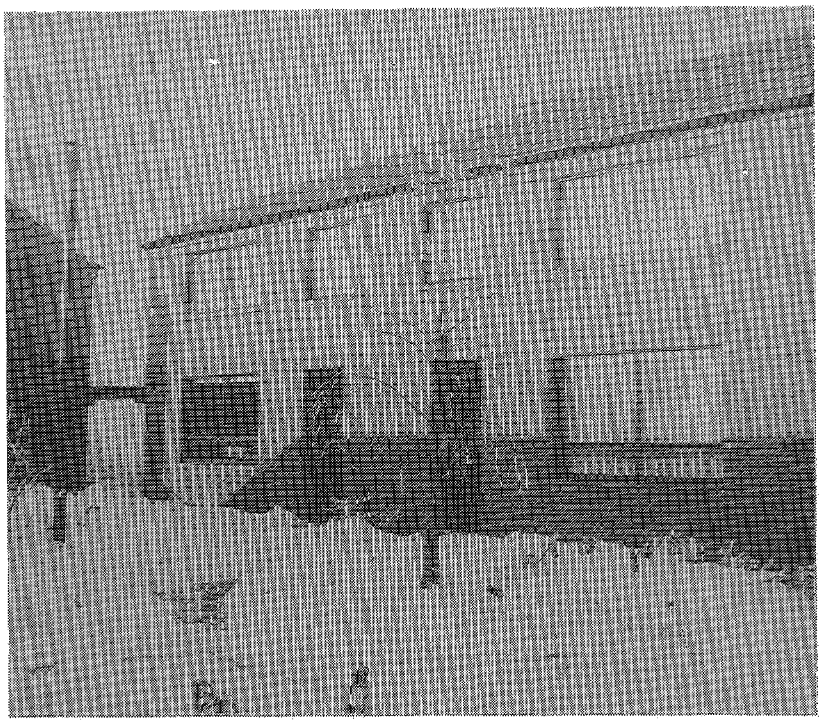


Figure 2.8 A typical Pennyland south facade

Note shadow of roofline on wall. Time 2.0 p.m. on a January afternoon.

### 2.3.4 Effects of orientation

Initially it was felt that all the passive solar houses should face rigidly south, a point that produced rather drab estate layouts and caused considerable friction between architects and scientists. Computer modelling of the relation between space heating consumption and house orientation showed that the optimum house orientation was slightly east of south, but that the range of permissible orientations was quite wide, south ± 45° being specified for Pennyland and ± 30° for Linford.

This freeing from an orientation constraint was probably the most useful result of the computer modelling at the design stage and allowed a much more creative layout for the Pennyland estate.

The wide range of permissible orientations also applied to the solar water heaters then considered, orientations of south ± 45° only involving a performance reduction of 10% (see Reference 2.13).

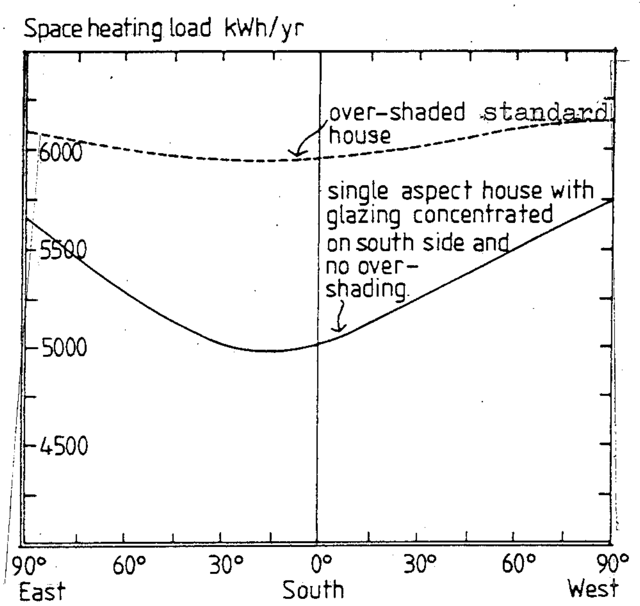



Figure 2.9 Original estimates of variation of space heating energy consumption with orientation

Pennyland style house.

See Chapter 10 for a post-experiment estimate for Linford

### 2.3.5 Effects of window area and position on heating requirements

Assessing the effects of window areas, both on the north and south sides of a house on space heating energy consumption is a rather complex process. It depends on the glazing type, single or double glazed, and whether the window is insulated at night. It also depends on how long the heating season is,

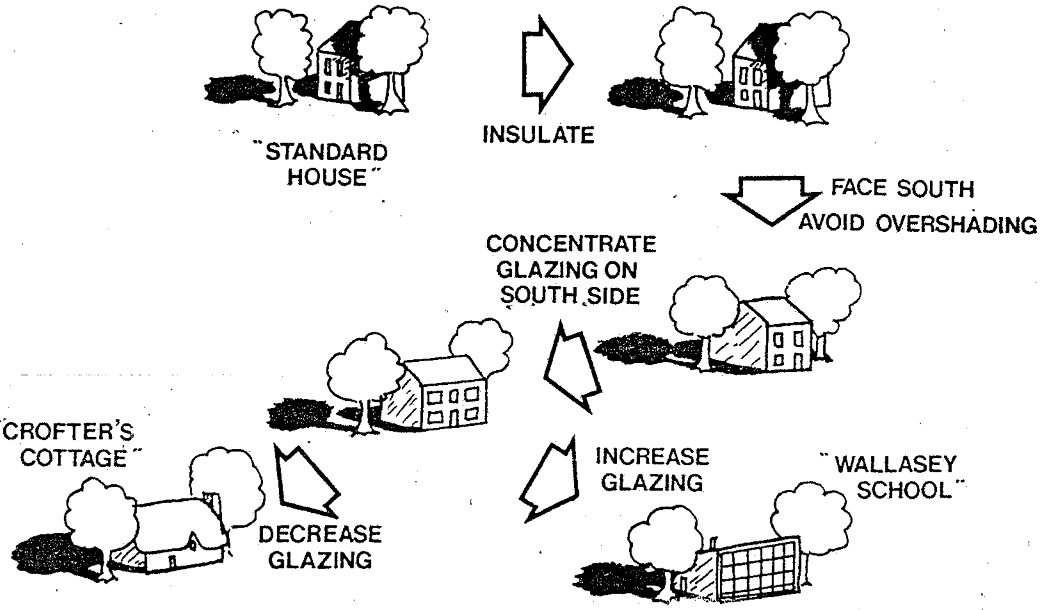



Figure 2.10 House analysis sequence

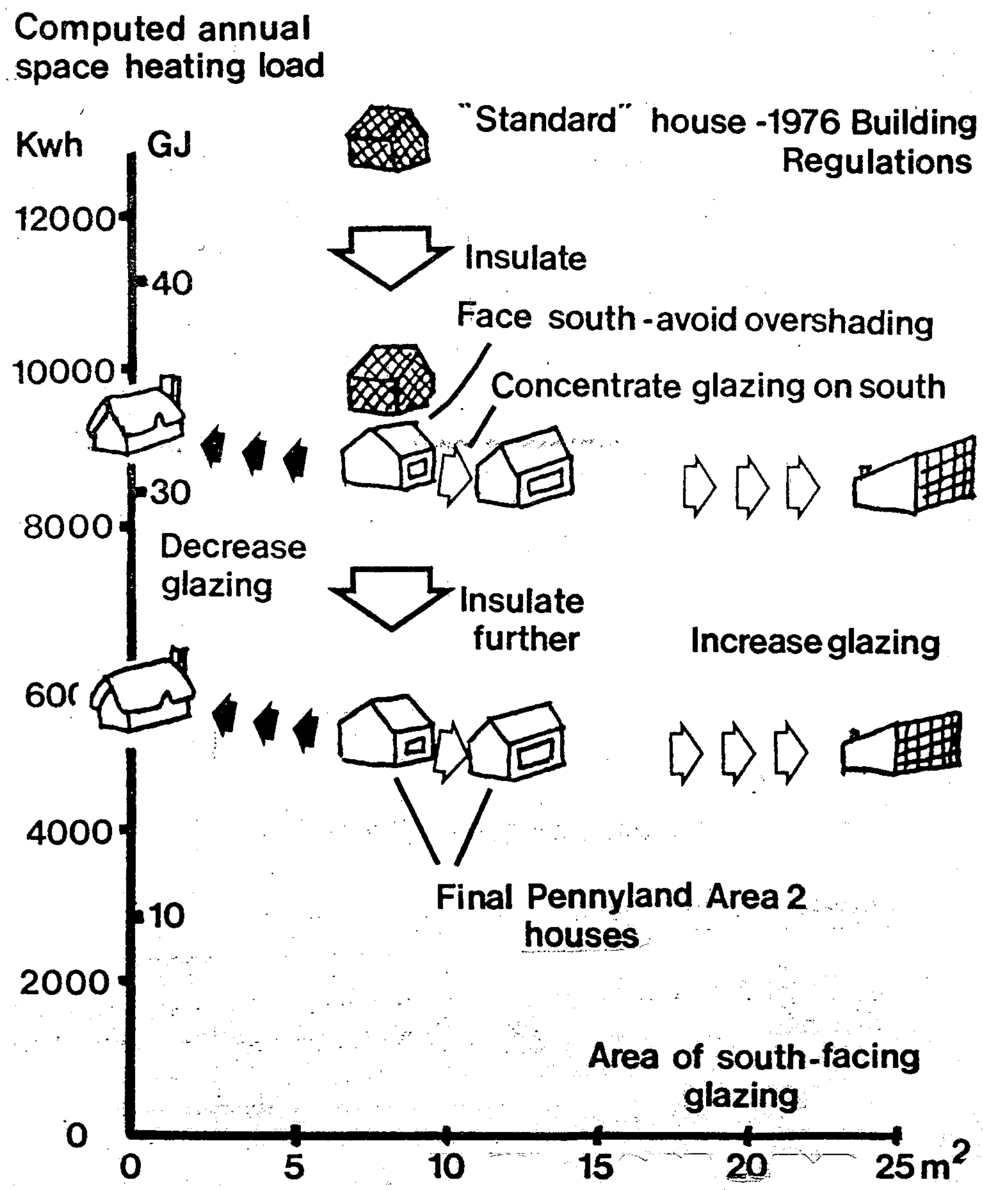



Figure 2.11 Effects of window area and position on energy consumption

whether it is restricted to the dull mid-winter months or whether it extends into the sunnier months of September, April and May. This, in turn, depends on the general insulation level of the house, on internal temperatures and free heat gains.

For the design process, the marginal solar gains of houses with single and double glazing were assessed by first choosing a self-consistent set of insulation measures that are likely to accompany each glazing standard. It would not, for instance, make much sense to install double glazing in a house with no loft insulation.

A series of house designs were evaluated using the NBSLD model, incorporating the best guesses that could be made about likely internal temperatures, free heat gains, etc.

The sequence of modifications is shown in Figure 2.10. Starting from an overshaded, randomly oriented, dual aspect house (one with glazing equally on both sides), the house is first insulated. Then the overshading is removed and the house oriented to face south. The glazing can then be concentrated on the south side, without increasing the total area. Next there is a choice of whether to increase the south-facing window area, leading to a Wallasey School type of design, or to decrease it leading to a 'crofter's cottage' design with almost no window area. The process of modifying the glazing area can be repeated again at a higher insulation level.

Figure 2.11 shows the effect of window area and position on space heating for three levels of insulation:

A. 1976 Building Regulation standard, 50 mm roof insulation, single glazing, unfilled cavity wall, U-value 1.0 $W/m^2 \,^oC$.
B. Approximate Pennyland 1/1982 Regulation standard. As above but with 50 mm cavity wall insulation.
C. Pennyland 2/Linford level. 150 mm roof insulation, double glazing, 100 mm cavity wall insulation.

The house type is assumed to be an end of terrace, 3 bedroom house similar to those actually built at Pennyland.

This graph illustrates clearly that the likely energy savings from insulation are much greater than those from changes in window area and position. Also it shows that there is little point in trying for 100% south-facing glazing area, since there are diminishing returns above about 40%. Further calculations suggest that the peak summer temperature in a house with 100% south-facing glazing would be about $3^oC$ higher than that in one with 40% glazing. As a result of these findings, coupled with cost considerations, the glazing area of both the Pennyland and Linford houses was kept below 50%.

Although no specific calculations were done for the Linford house design, it is likely that the energy benefits for the bigger house would be somewhat larger, with the total marginal passive solar savings due to avoidance of overshading, correct orientation and concentrating glazing on the south-side, being about 2000 kWh/yr of useful space heating energy.

Full details of these design calculations are given in Reference 2.12.

### 2.3.6 Thermal mass and summer overheating

Calculations of summer overheating showed that thermal mass was the most effective way of restricting peak temperatures without unduly increasing winter energy consumption (see Chapter 10).

The early house designs incorporated a balcony (see Figure 2.13) to act as summer shading, but the high cost and the possible detrimental effects on useful spring solar gains led to this being omitted.

Correct orientation was also found to be beneficial. Orienting the house south involved the minimum peak summer temperature. The worst orientation from this point of view was due west, when the large glazing area of the house would catch the sun at the end of a hot summer afternoon.

## 2.4 <u>The practical housing schemes</u>

### 2.4.1 Woughton 'D' and Linford

It was originally intended to build two estates of low energy houses. The first, known as Woughton 'D', was to be of 10-12 houses, to be intensively monitored and originally to be built in late 1977. This would have acted as a pilot project for the larger Pennyland scheme, then scheduled to start in 1980.

Designs for the Woughton houses were produced in 1978 by architect Martin Richardson. The floor plans (see Figure 2.12) were essentially very similar to those eventually used at Linford.

The Woughton site eventually proved to be too 'up market' for an experimental project and it became necessary to approach a new developer, S. & S. Homes for another site in 1979. By this time the design requirements had been clearly set out, and it was possible to give the new developers a clear energy brief, as listed at the beginning of the next chapter.

The Woughton designs were incorporated in the Guildway range of houses and Figure 2.13, showing their 'Doon' design, gives a good impression of what the Woughton houses would have looked like, including the summer shading balcony.

### 2.4.2 Pennyland and Neath Hill

While the Woughton/Linford 'pilot' was progressively delayed, the large scale Pennyland project was actually brought forward in time to start at the end of 1979. Design work for this estate thus proceeded quite intensively during 1977 and 1978. The large number of houses involved meant that cost-effectiveness had to be taken very seriously and this was reflected in the energy brief for Linford.

Since this project will be mentioned quite frequently in this report it is worth giving a brief description of the estate and the monitoring project, though for full details it will be necessary to refer to the companion Pennyland final report.

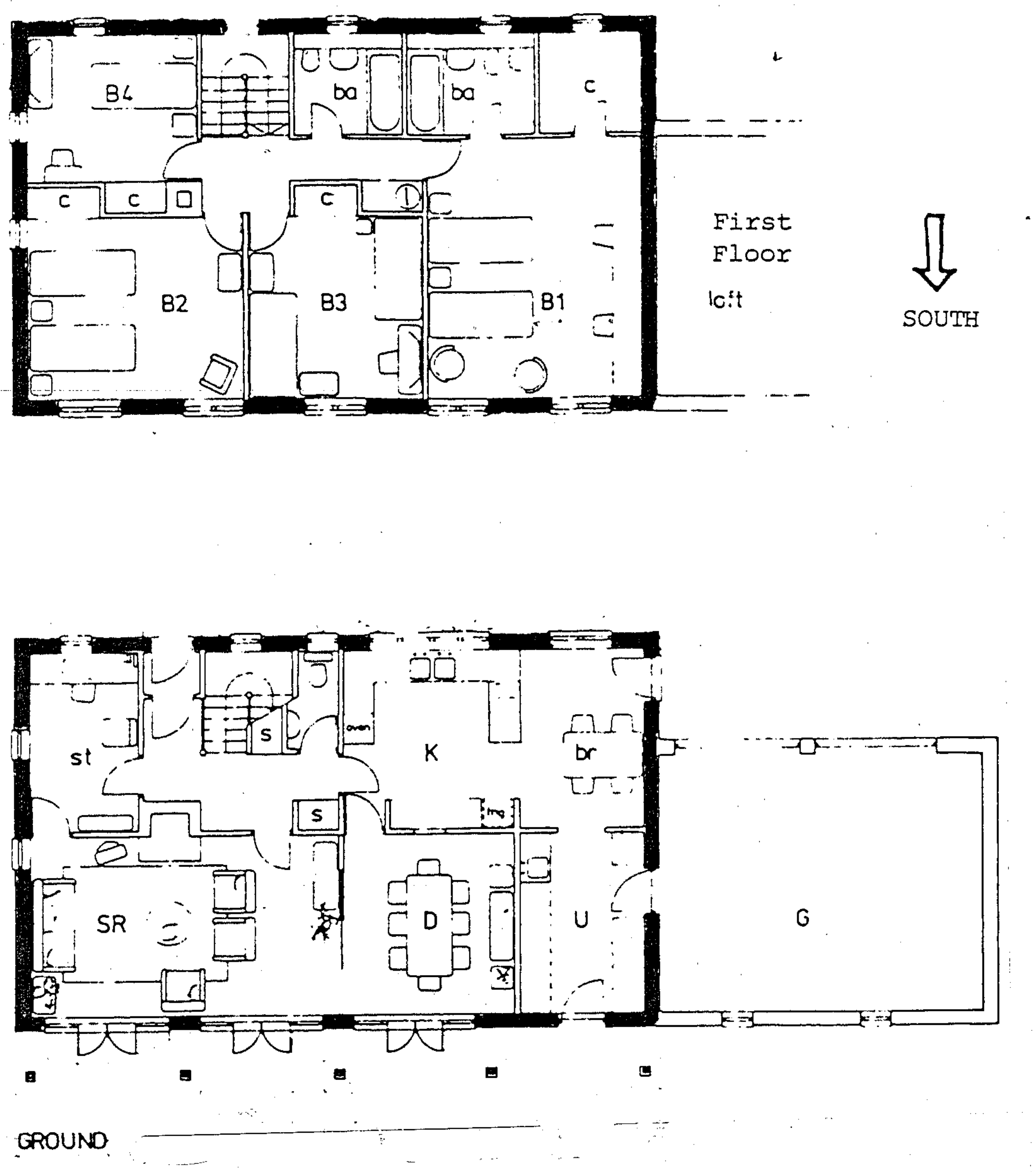



Figure 2.12 Woughton 'D' floor plans

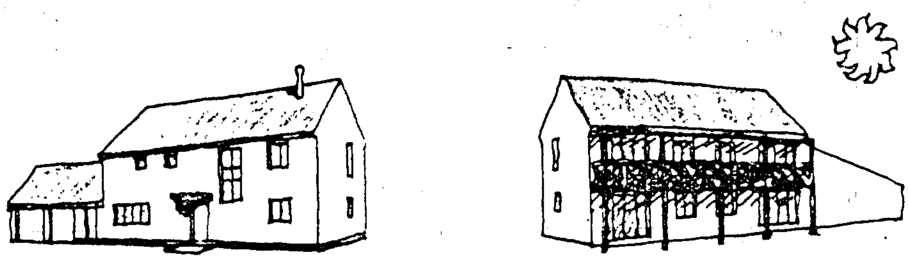


Figure 2.13 Guildway 'Doon' design - similar to original Woughton design. Note balcony for summer shading.

Drawings courtesy of M. Richardson.

The Pennyland estate as built consists of 176 houses laid out using the solar shadow prints to avoid overshading (see estate plan Figure 2.14).

The estate is split into two halves, each with a different insulation level:

Area 1: Single glazing
50 mm cavity wall insulation
80 mm roof insulation

Area 2: Double glazing
100 mm cavity wall insulation
150 mm roof insulation

The two areas thus correspond roughly to the 1982 Building Regulation standard and the Linford standard.

Within each area, the most common house type, a 3-bedroom house of 90 $m^2$ floor area, was built in two variants, a dual aspect version with 7.4 $m^2$ of south-facing glazing, and a single aspect version with 13.6 $m^2$ south-facing glazing and very small windows on the north side. The Area 2 single aspect houses are thus very similar in design to the Linford houses, although with a smaller window and floor area. The Linford houses have a floor area of 110 $m^2$ and a south-facing window area of 21.7 $m^2$.

For comparitive purposes the neighbouring estate, Neath Hill, built in 1978, was taken as a control. In order to act as a 'solar' control group, a number of Neath Hill houses were given foam cavity fill insulation. This thus added two more insulation levels to the list for comparison:

Neath Hill Uninsulated: No cavity insulation
50 mm roof insulation
Single glazing

Neath Hill Insulated: 50 mm cavity insulation
50 mm roof insulation
Single glazing

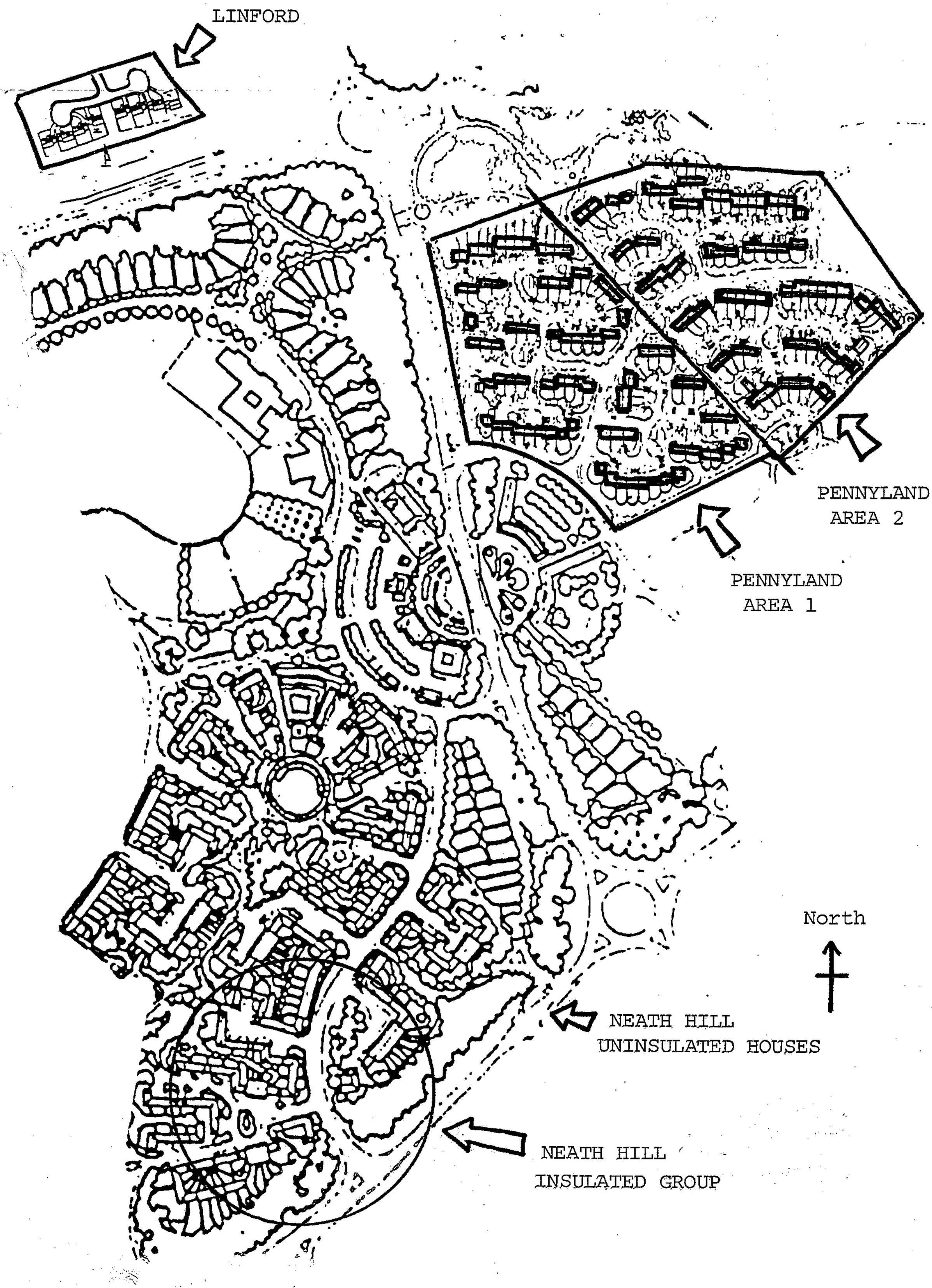
Another major difference between the Pennyland and Neath Hill estates was the choice of boiler. Neath Hill was equipped with a conventional heavyweight boiler. Pennyland (and Linford) were equipped with a high efficienty low thermal capacity boiler. There have also turned out to be marked differences in air leakage between the two estates.

Monitoring was carried out on a much simpler basis than for Linford. For most of the houses, gas and electricity meters were read monthly. For 80 houses, 60 in Pennyland and 20 at Neath Hill, extra monitoring equipment was installed to measure space heating energy and, in some houses, water heating energy. Other equipment gave readings that could be read on meters outside each house by a visiting meter reader, once a week.

Analysis of the data from this project has mainly taken the form of statistical comparisons of energy consumptions from various groups, corrected for minor differences in house heat loss, number of occupants, etc. The project is thus complementary to Linford, which is mainly concerned with the detailed breakdown of energy flows within houses.

Some of the results from Pennyland, in particular estimated boiler

Figure 2.14 LINFORD AND PENNYLAND PROJECT HOUSES



efficiencies and pressure test air leakage rates, have been incorporated in this report. Also, the use of net curtains on Pennyland is likely to be a better indicator of general use than the Linford houses, which are not overlooked on the south-side and do not have typical privacy problems.

In general, the Pennyland project has provided a convincing demonstration of large energy savings due to the measures incorporated in the Linford houses, while the Linford project itself gives a more detailed picture of their breakdown.

## 2.5 Overall timescale

Although most of this report is about the monitoring of the Linford houses, it should be stressed that the total timespan of the project from the beginning of research work to this final report is over 8 years. Figure 2.15 shows the stages that the Linford and Pennyland projects have passed through from the founding of the MKDC Energy Consultative Unit to the final project reports. The total research expenditure on the two projects approaches £300,000, from a variety of sources and represents about 15 man-years of research work.

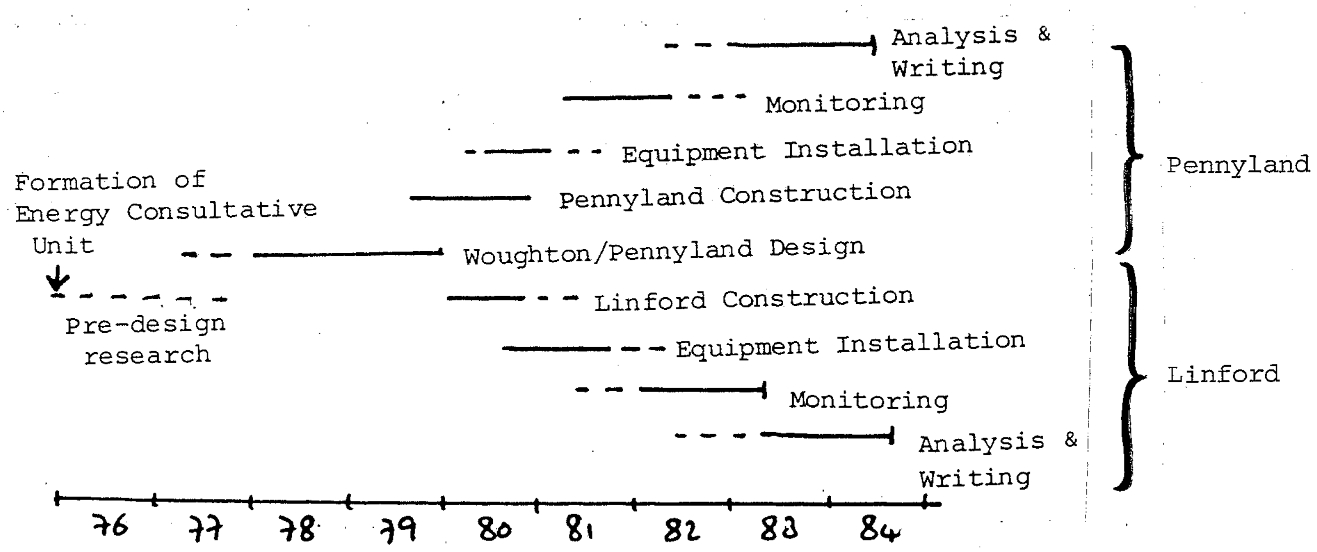



Figure 2.15 Overall project timescale

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# 3. THE HOUSE DESIGN

CONTENTS



The energy saving features incorporated into the Linford houses are described and their effect on the detailed design of the houses is illustrated.

# 3. HOUSE DESIGN

## 3.1. Introduction

In spring 1980 design work started in earnest on the Linford Project. The intensive design and modelling work previously carried out for Pennyland proved to be a useful guide to the measures that were likely to be cost effective at Linford. The requirements and guidelines were drawn up as a two-page brief. The main points were to:

1. Face the houses within ±30° of south.
2. Use a single aspect house design.
3. Plan living and bedrooms on south side and with the kitchen, bathroom and circulation placed on the north side.
4. Avoid overshading on the south side.
5. Provide 15-20m² of glazing on the south side.
6. Reduce glazing to a reasonable minimum on the north side.
7. Use dense concrete blocks for inner leaf and partitions on ground floor, and upper floor when there is a partition underneath.
8. Insulate cavity with 100mm insulation.
9. Insulate perimeter of ground floor slab, 900mm wide, 25mm thick.
10. Loft insulation to be 140mm.
11. Provide draughtstripping.
12. Use a cheap form of double glazing.
13. Provide blinds or other night insulation.
14. Use a low thermal capacity boiler.
15. Zone heating of upper and lower floors.
16. Use hybrid controls systems with room thermostat in living room and thermostatic radiators valves (TRVs) in other rooms.
17. Ensure roof ventilation is provided (10mm minimum along eaves or equivalent area).

The reasons for some of these items are clear, others need some explanation. The reason for the 15-20m² of glazing specified on the south side was because computer simulation showed that benefits were slight or even negative after glass area was increased beyond 20m². Dense concrete blocks on the inner face of the external wall and for partitions were recommended, to provide some thermal mass and prevent overheating.

The insulation levels were set as much by practical concerns as theoretical. Wall insulation was confined to 100mm because this cavity width is the maximum allowed under the deemed to satisfy provisions of the Building Regulations, while the loft insulation thickness of 140mm was the maximum manufactured, and there was some concern that condensation risks would be greater beyond this thickness. 25mm of perimeter floor insulation was chosen because according to the CIBS guide, the effect of insulation on floor U value was small. Therefore, only a small thickness appeared cost effective. Cheaper forms of double glazing were specified because the conventional forms were shown not to be cost effective in computer modelling and QS costing.

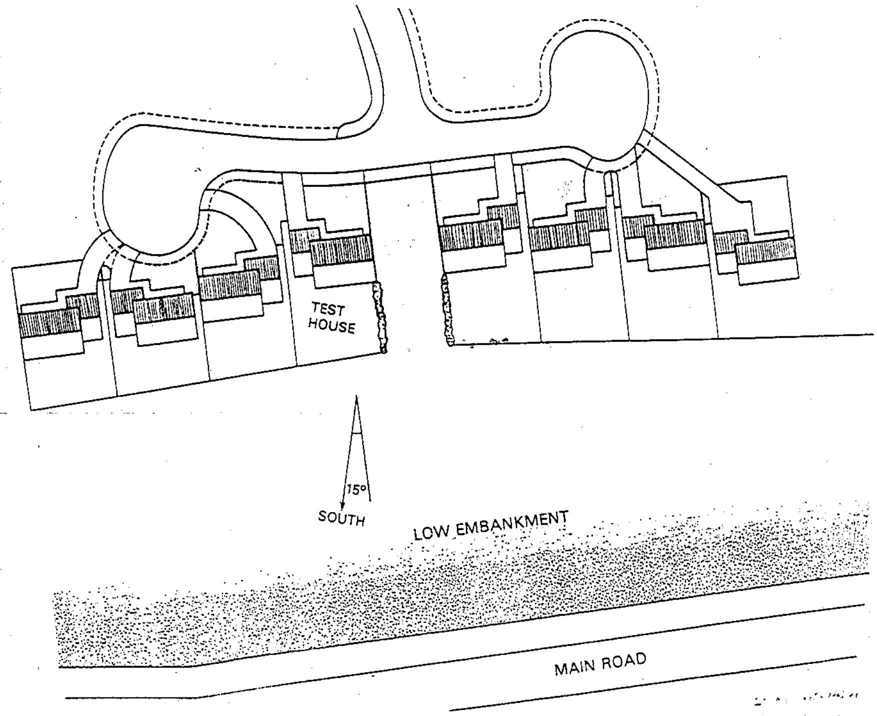



Figure 3.1 Site Plan

## 3.2. House Design.

Using this brief, and the requirement by the developer for four-bedroom houses, the architect provided an initial design in two days. This design incorporated all the features outlined in the Energy Brief. The design was to all intents and purposes the house that was built, except that the north facing windows were a little larger. This impressive speed seems to show that the energy brief was easy to assimilate.

The house plans, sections and elevations are shown in Figures 3.2-3.4 and Appendices 3.1-3.4. Major rooms face south, with the exception of the fourth bedroom. It seemed reasonable to accept this since this room is likely to be used as a spare bedroom and would therefore only be intermittently heated.

There are draught lobbies on the north facing doors, but none on the south side, because of the difficulties of incorporating this in the design and the cost of construction. Again it seemed reasonable to accept lobbies on one side only.

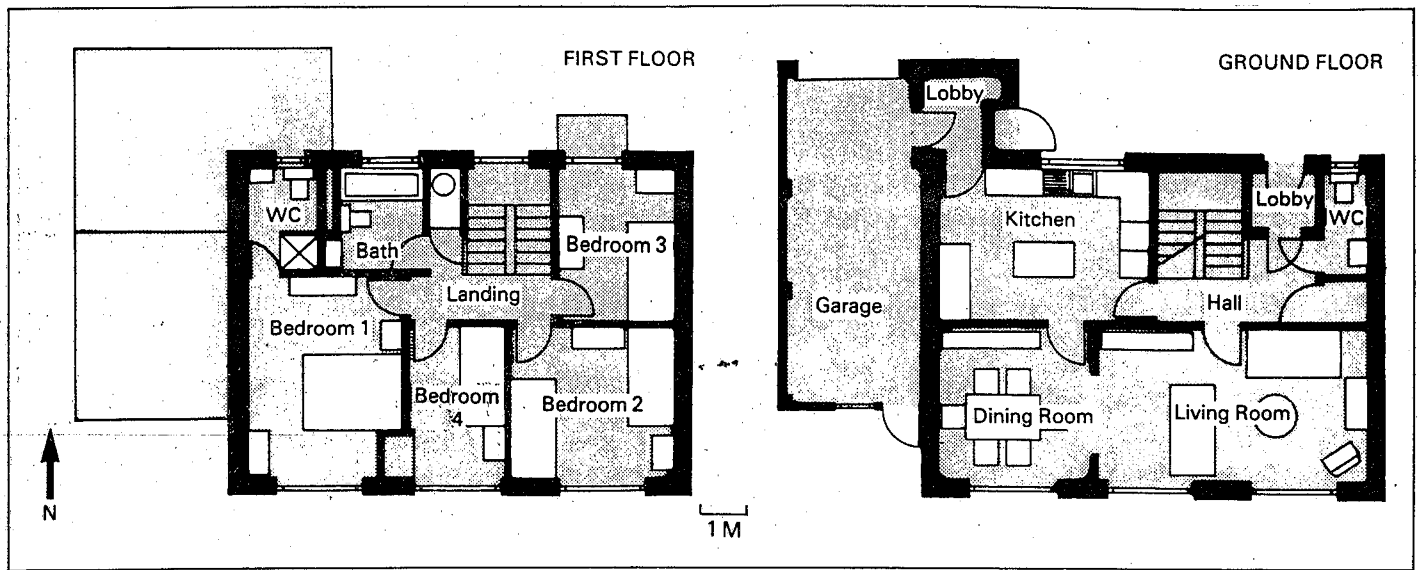



Figure 3.2 House plans

Eight houses were built to this design, laid out as shown in Figure 3.1. The houses are detached and face 15° east of south. There is an embankment to the south with the top forming an angle of 5° to the horizontal, relative to the bottom of the ground floor windows.

The overall plan dimensions of the houses were 8.7 x 6.3m internally, and the floor to ceiling heights were 2.4m. The areas and U values of the elements of structure are given below.

| Element | Area $m^2$ | U-Value $W/m^2\,°C$ | Description |
|---|---|---|---|
| Floor | 55 | 0.5 | 25mm perimeter insulation, concrete slab |
| Walls | 132 | 0.3 | 100mm brick, 100mm insulation, 100mm block |
| Roof | 55 | 0.3 | 140mm insulation, timber and tile sloping roof |
| Windows - south | 17.8 | 2.5 | sashless double glazing |
| Doors - south | 3.8 | 3.0 | double-glazed french doors |
| Windows - north | 5.9 | 2.5 | sashless double glazing |
| Doors - north | 3.6 | 3.0 | timber cored door, draughtstripped |
| Volume lac/hr | $263m^2$ | 0.33 | |

Table 3.1: Element areas and U values

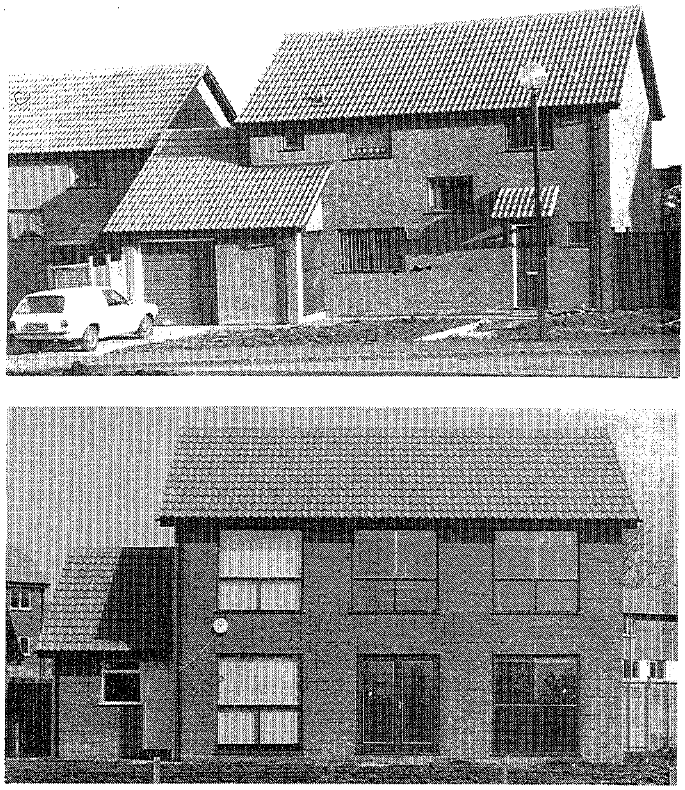


Figure 3.3 Great Linford houses : North (top) and South (above) elevations

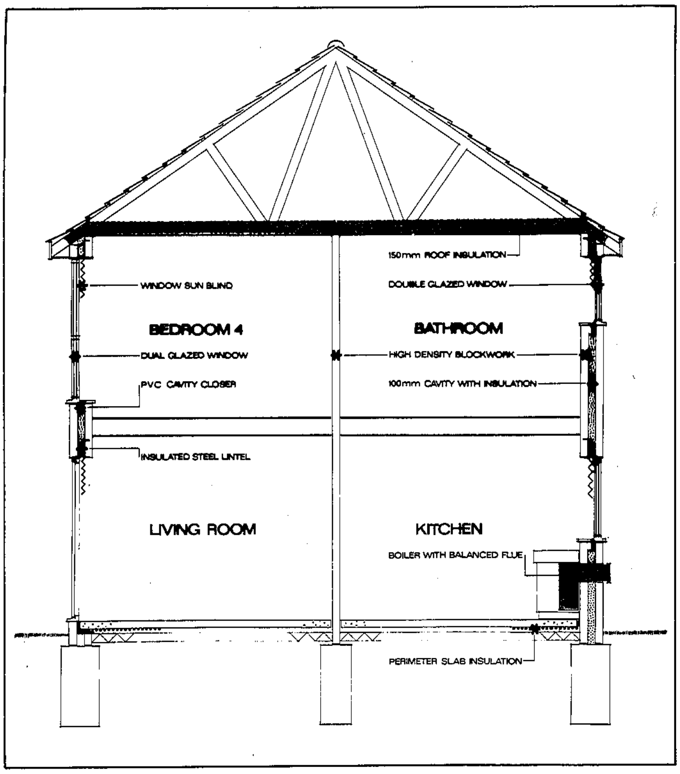



Figure 3.4 House section

## Construction Details.

Details are shown in Figure 3.5. The construction is as follows:

1. Structure.

The house is constructed of traditional brick and block with 100mm cavity, and with concrete ground floor, timber first floor, and timber trusses supporting concrete tile roof. 100mm dense concrete blocks have been used for the inner leaf of the outer wall, for ground floor partitions, and for upper floor partitions where they are supported by ground floor partitions. Ventilation of the roof space is provided by four 225 x 225mm air bricks, two in each gable end wall.

2. Windows.

The double glazed windows are made by the Sashless Window Company, and are the largest units that they manufacture. There was some difficulty with their performance, which is discussed later in the Buildability Section. They are well draught sealed, and are rated for severe exposure. Dacatie cavity closers were used around window openings.

3. Insulation.

The roof insulation is normal glass fibre roll insulation 140mm thick, laid between the joists, while wall cavities are completely filled with 100mm thick Pilkington Drytherm insulation batts. Wall ties are galvanized vertical twist type at 450mm centres vertically and 750mm horizontally. (Butterfly ties are not permitted in the deemed to satisfy section of the Building Regulations). Floor insulation is 25mm thick Jablite flooring grade, laid 900mm round the perimeter of the slab, and between slab and blinding. The insulation turns up at the edge of the floor, and is masked by the plaster and skirting board. The boards are laid over the D.P.M.

4. Blinds.

Pleatex corrugated paper blinds, manufactured by R.F.Sampson Ltd., were fitted to give some night window insulation and to reduce solar inputs on sunny summer days.

5. Heating System

Space heating was provided by a wet radiator system, heated by a central boiler. The boiler was a low thermal capacity Chaffoteaux Maxiflame 2. A small boiler was initially suggested but concern over the sizing procedures for highly insulated houses led to the use of a more conventionally sized one. The heating controls were arranged so that the boiler and pump were both switched off if both the zone thermostats and the boiler thermostats were satisfied; this avoided boiler short cycling.

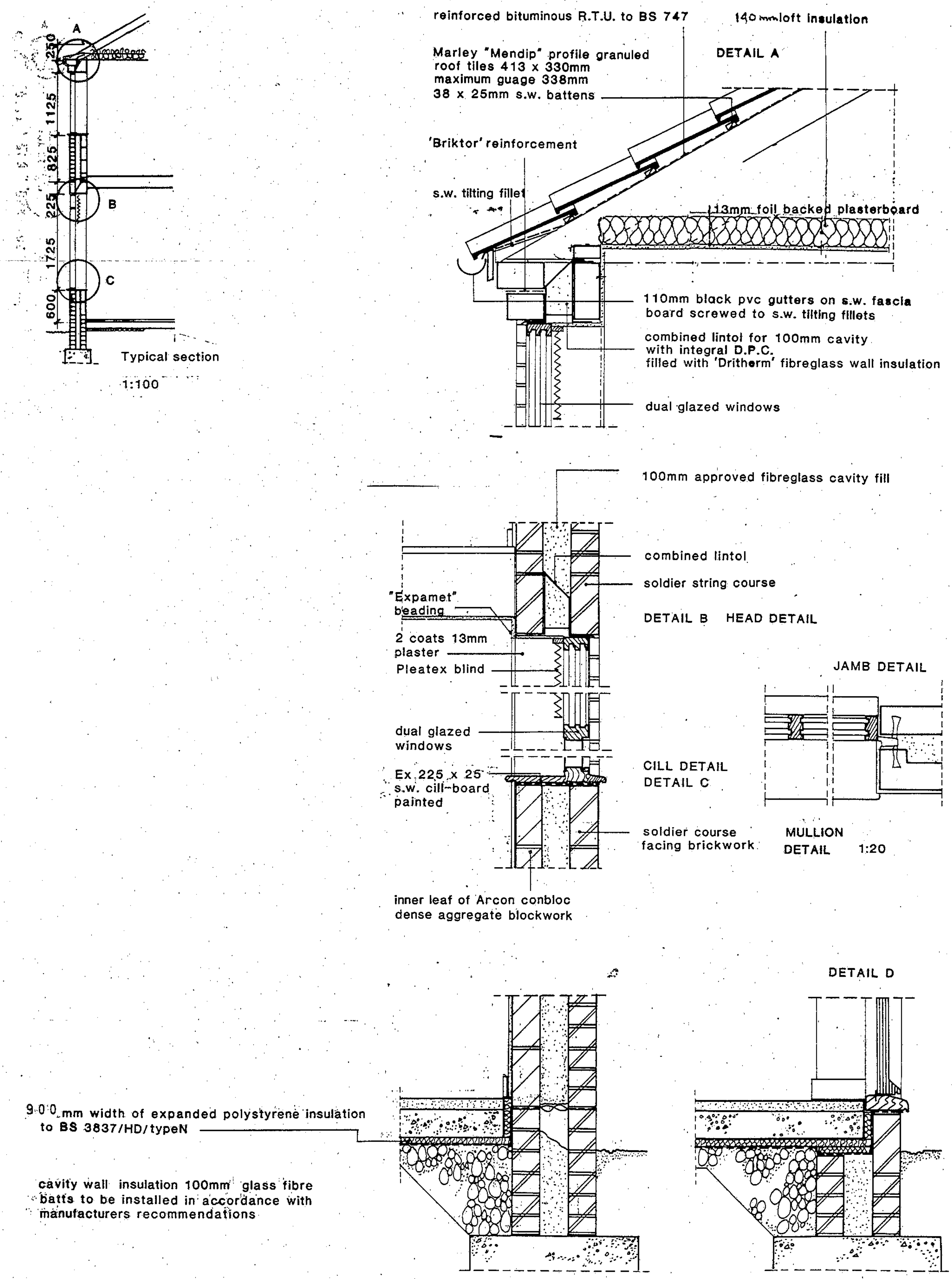
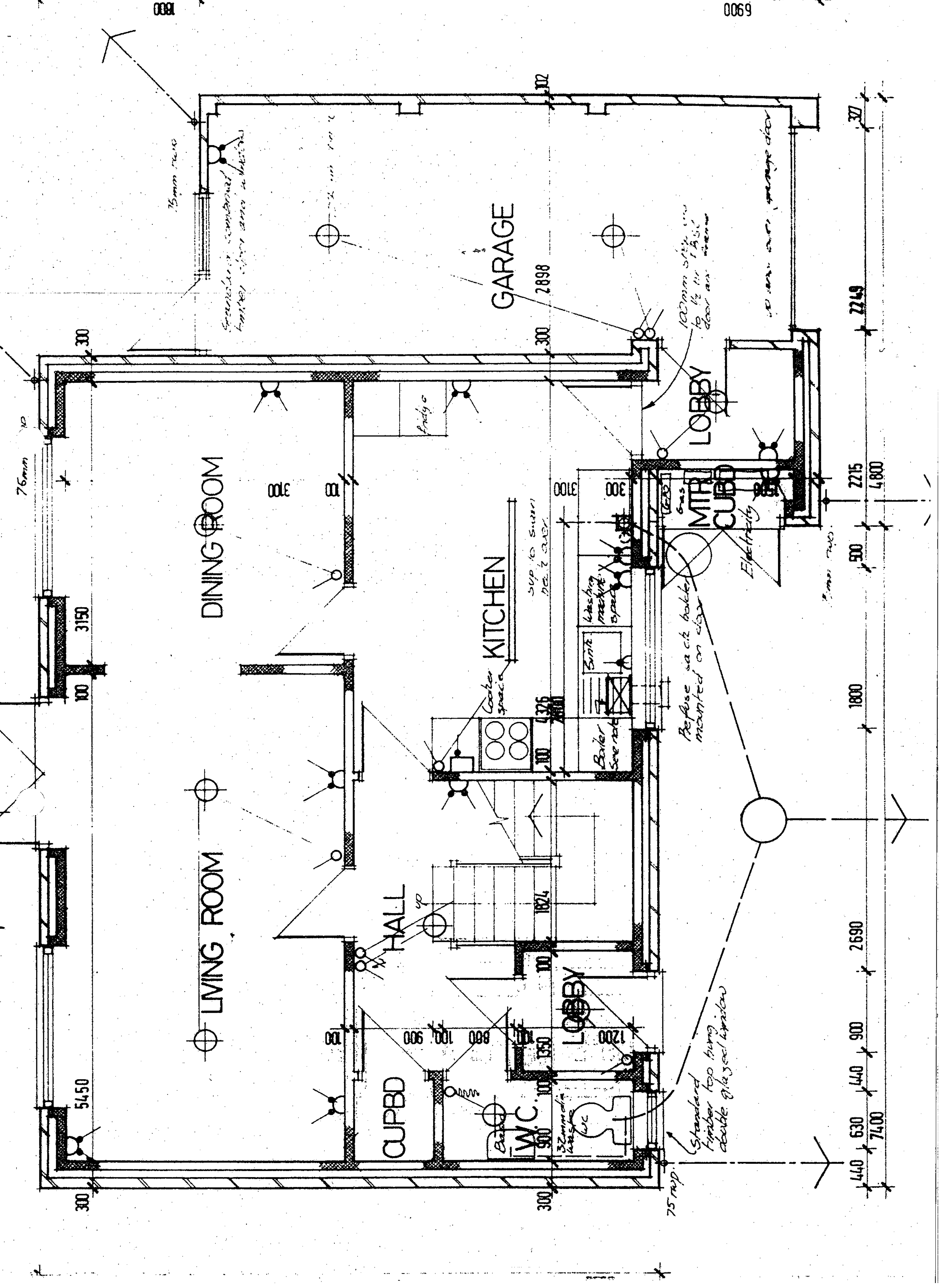
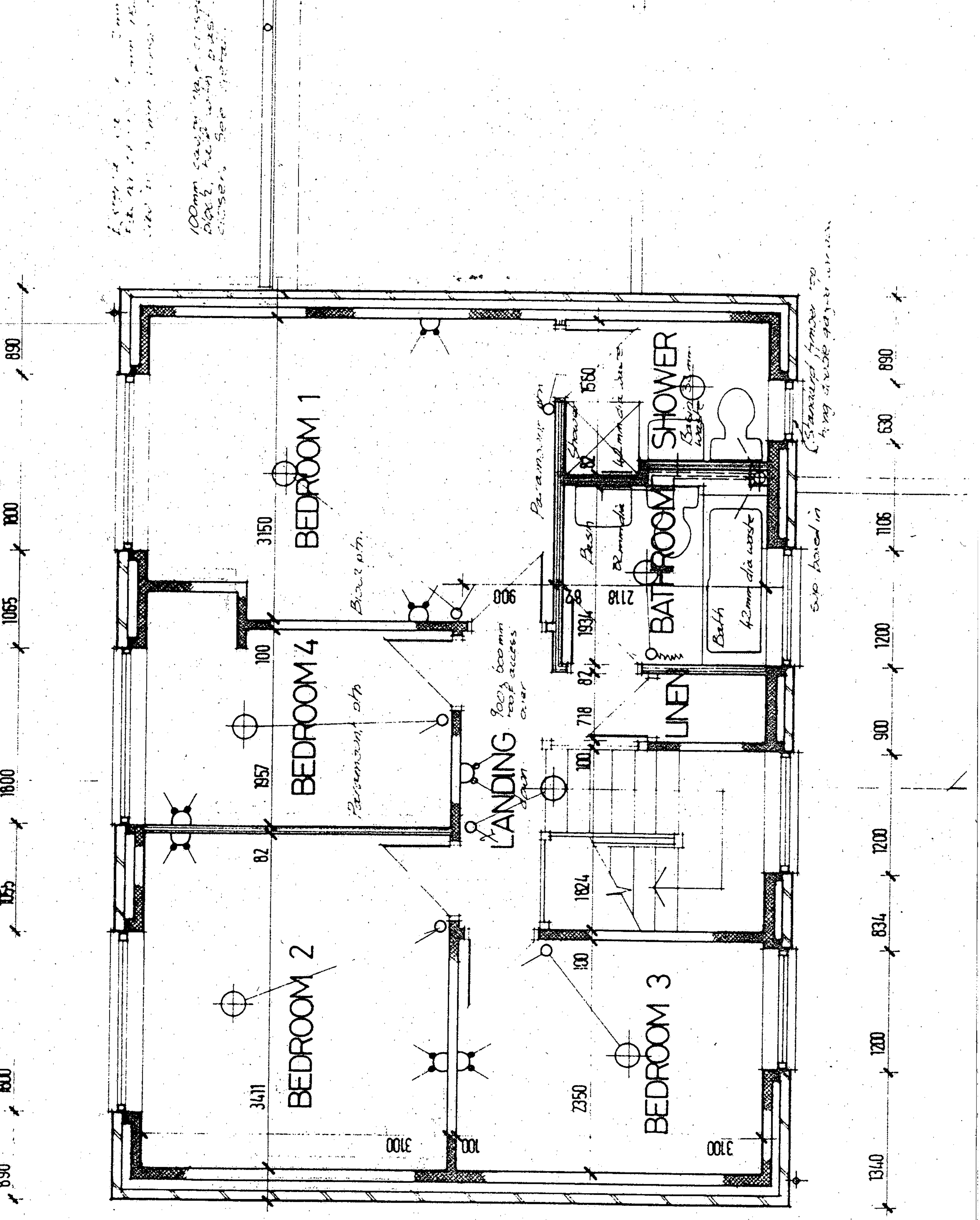



**Fig. 3.5** ASSEMBLY DETAILS

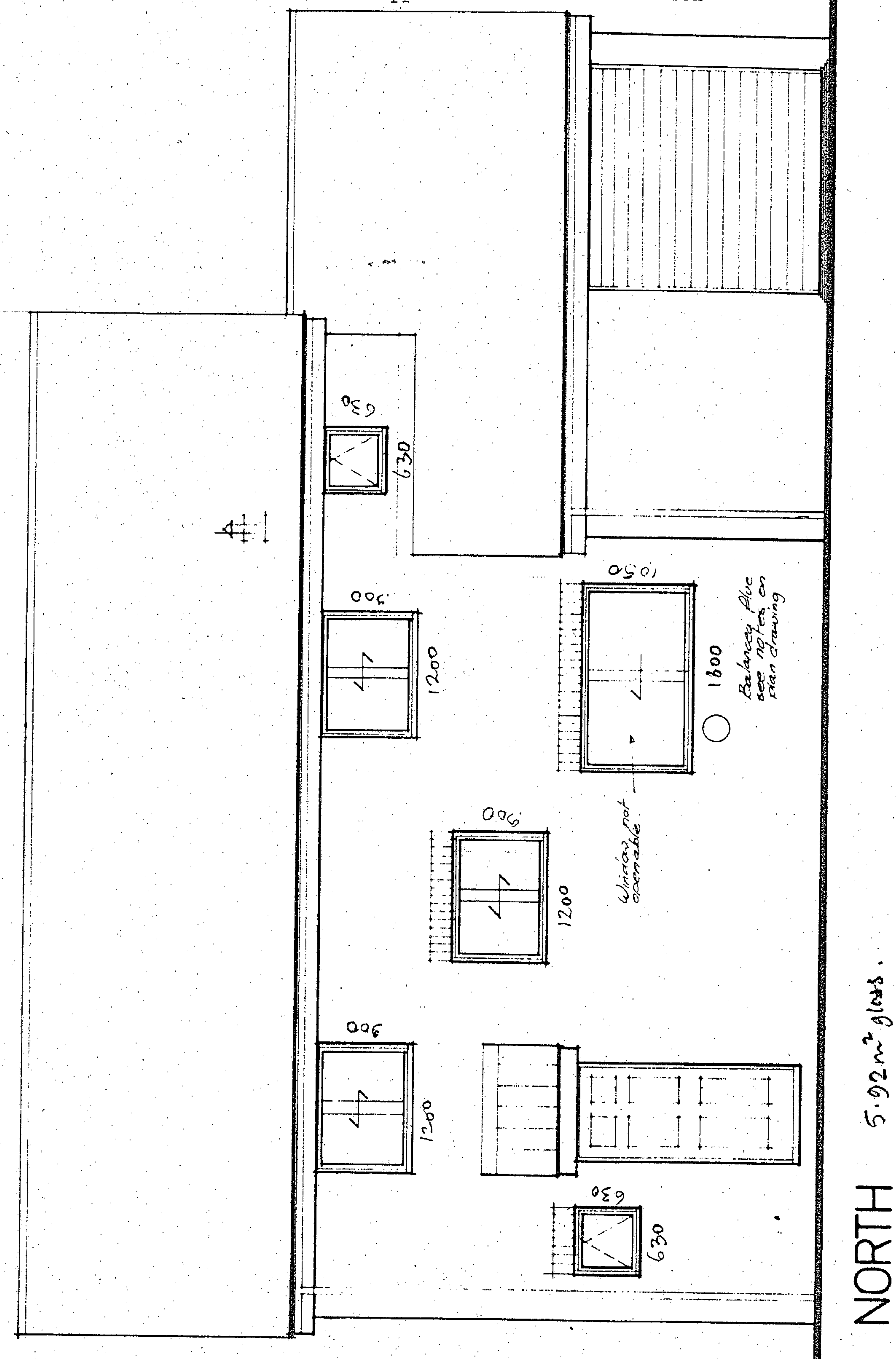
Appendix 3.1 Ground Floor Plan



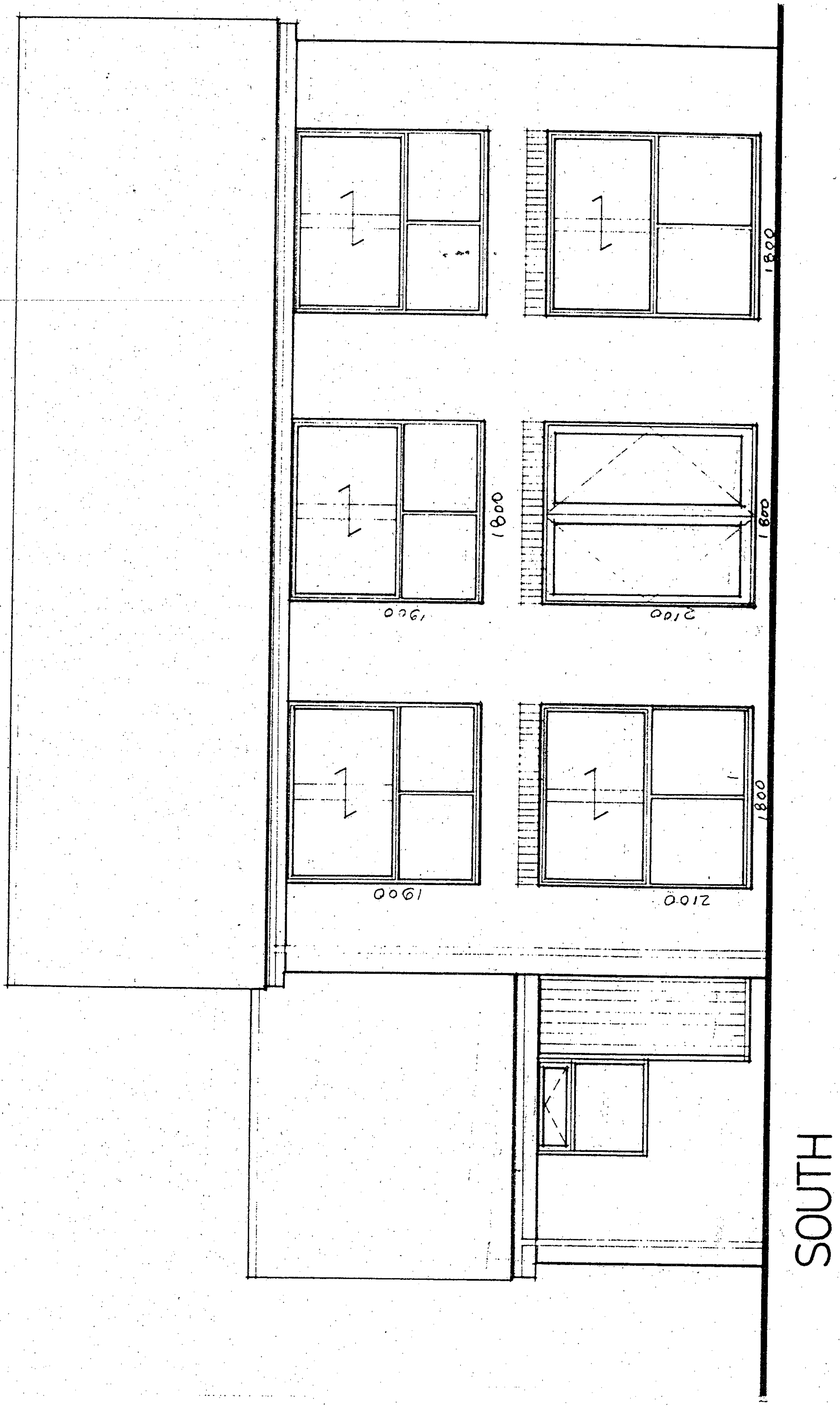
## Appendix 3.2 First Floor Plan



Appendix 3.3 North Elevation



Appendix 3.4 South Elevation




Glazed Area: S. 21.6m² inc glazed door.
N. 5.92m²

# 4. BUILDABILITY & DESIGN EXPERIENCE

CONTENTS



The ease by which the energy conservation measures were incorporated into the construction was monitored by the Building Research Establishment. This chapter reports on the results of this buildability study together with a discussion of the lessons learnt from the design experience.

# 4. BUILDABILITY AND DESIGN EXPERIENCE

## 4.1. Introduction

During the design stage, there was some concern that the introduction of novel building techniques would introduce technical difficulties which would seriously affect overall building performances. There was some concern too that these techniques would result in greater expense than that allowed by the builder. It was therefore decided that one of the aims of monitoring would be to check the buildability of the extra insulation measures during the construction of the buildings. This part of the monitoring work was carried out by the Building Research Establishment. As a result of the design and construction experience, several lessons were learnt, and these are also discussed.

## 4.2. Buildability.

The houses were constructed from September 1980 to December 1981, with a long delay in mid construction because of the slow market conditions at that time. The ease of construction was monitored by the Building Research Establishment at the same time as the much more closely monitored buildability studies on the nearby Pennyland Estate (Reference 4.1).

Construction was generally carried out as detailed, and no major snags were encountered. The floor insulation was the first insulation measure to be installed. Some concern had been expressed that the light insulation slabs would float to the surface of the concrete or blow away. In the event, small piles of wet concrete were used to hold them in place temporarily just before the main concrete was poured, and no difficulty was experienced.

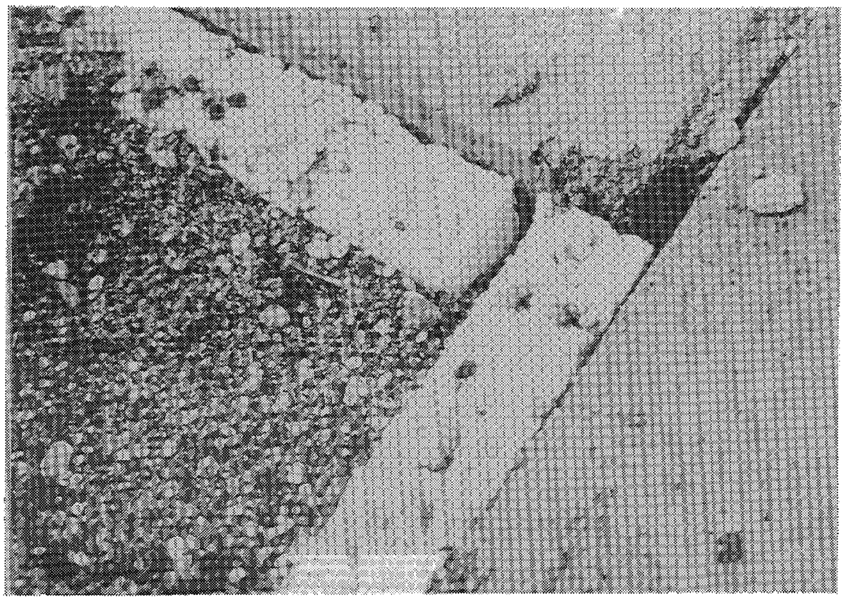


Figure 4.1 Slab edge insulation

Wall insulation was the next measure to be installed, and here there were some problems. The first was that mortar would inevitably build up on the top of the insulation batt during construction, unless a temporary board protected it. This proved almost impossible to supervise, and training of bricklayers is essential if this detail is to be satisfactory. The problem is that if mortar does get on the batts it can form a bridge for water to cross the cavity, and although there has been no sign of water penetration there were several cases when mortar snots were noted on the top of the batts.

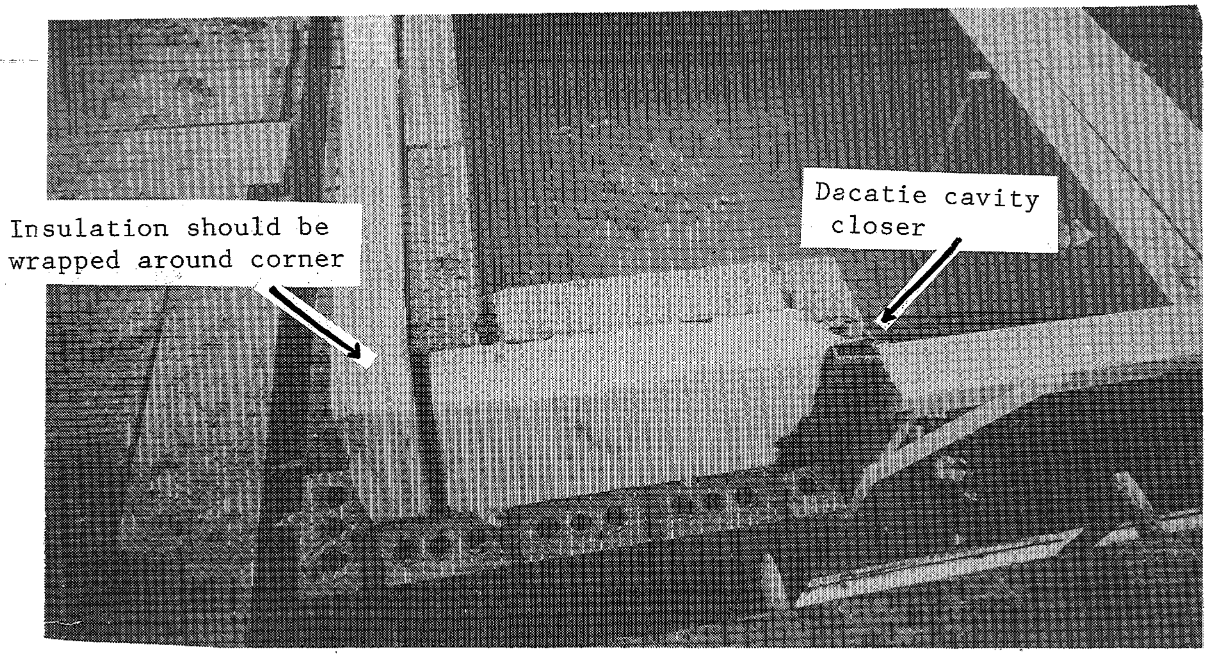



Figure 4.2 Wall insulation

The second problem was that in some places insulation was placed 'end grain' across the wall cavity, generally to fill in small areas or at corners. This is not acceptable, because the insulation is quite pervious in this direction and can therefore form a bridge for water. This was put right where possible, but again this detail is difficult to supervise, and also needs training of bricklayers. Insulation should be wrapped round corners to avoid this problem. At the base of the wall the insulation batt resited on the bottom wall tie, so avoiding the end grain of the batts being exposed to possible water build-up at the base of the cavity. There were no problems with the roof insulation.

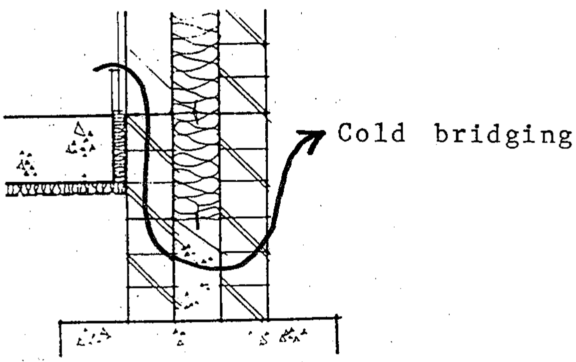



Figure 4.3 Wall insulation base detail

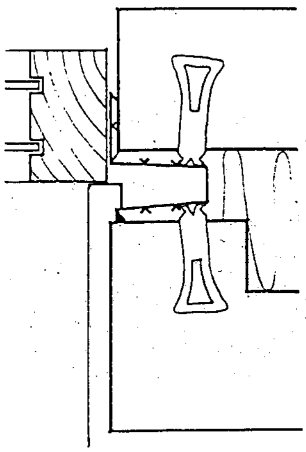


Figure 4.4 Dacatie cavity closure detail

Windows were fitted without problem, using Dacatie cavity closures to provide a good seal between frame and brickwork. This is a plastic strip fitted to metal ties that are set into the wall (see figures 4.2 & 4.4). This detail looks untidy from the outside of the house, but appears to work well in practice. Windows arrived with adequate protection to the vulberable sliding tracks.

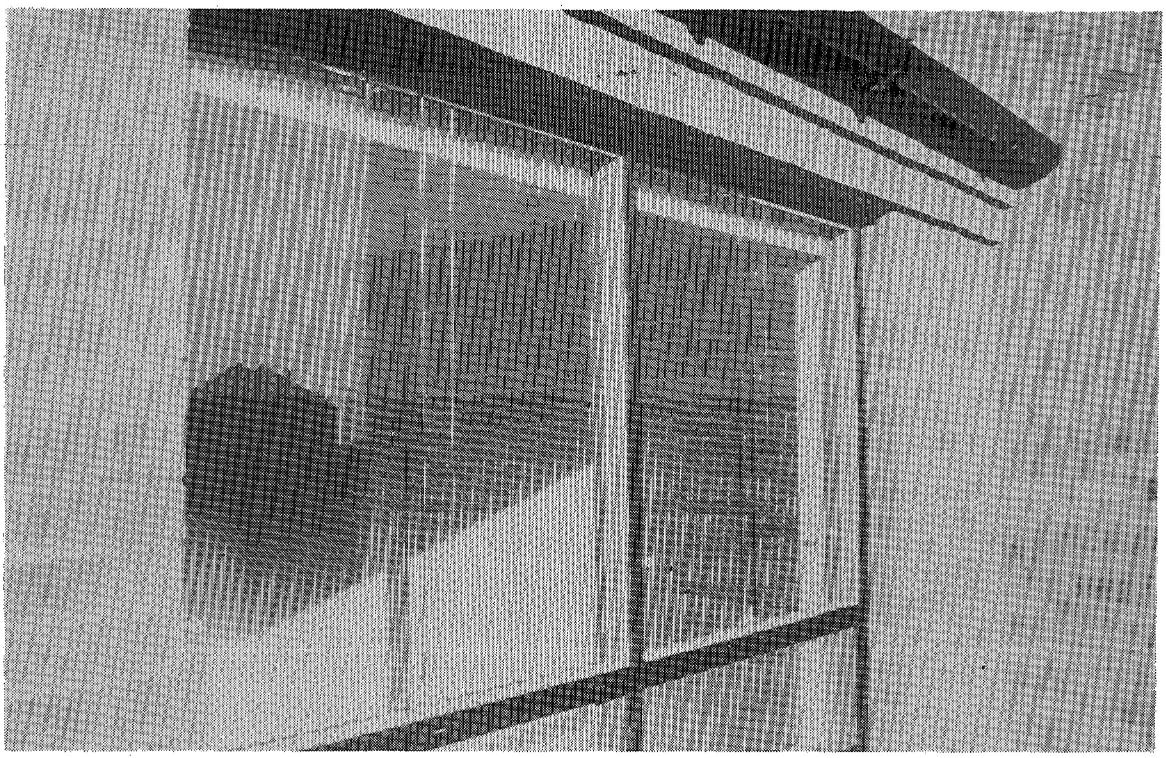


Figure 4.5 Sashless double glazing

The windows came with integral draughtstripping, but the doors were installed without draughtstripping, which was subsequently fitted by the researchers. The type of strip was Atomic plastic, a kind of flexible wiping blade and was quite awkward to install satisfactorily. The compressible hollow plastic tube variety of draughtstripping would probably be better (see Figure 4.7).

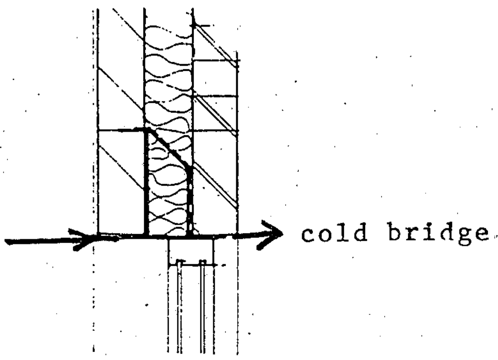



Figure 4.6 Lintel detail

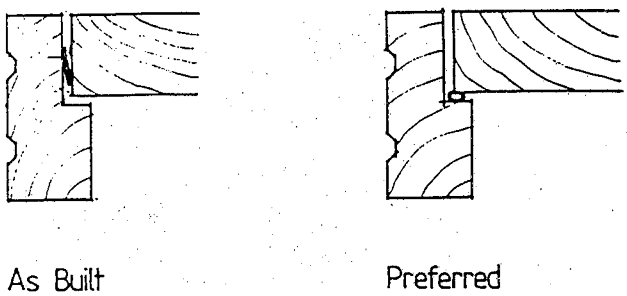



Figure 4.7 Door draughtstripping details

The problems outlined above were relatively minor and buildability was generally satisfactory. Evidence of this was given in the thermographic survey carried out in November 1983, which showed that thermal insulation had performed satisfactorily, except for a small part of the roof insulation. This survey is described in detail in Chapter 8.

## 4.3 Design experience

The BRE found that the novel features were generally easy to incorporate and did not produce significant difficulties, nor did they impede construction progress. However, a few difficulties arose which are worth noting so that they can be remedied in any subsequent building.

The first of these problems involves the use of Sashless double glazing windows. The subsequent performance of the windows has not been entirely satisfactory, with one occupant in particular very dissatisfied. The problem has been that grit is retained at the junction of the two glass panes, and scores the glass when the window is opened.

The problem does not appear to any great extent in other houses, and there is no evidence as yet that it occurs on the smaller windows at Pennyland. A partial solution was offered to the window suppliers by the OU, but as far as is known has not been acted on; this involved small alterations to the track and stick-on pads on the glass so that the two glasses separate earlier in the sliding operation. The window manufacturers have stated that this is a problem which occurs very rarely indeed, and there is no need to change their process.

There is also some misting in the unsealed cavity; this appears to be a visual nuisance. There is no knowledge of the opinions of Linford occupants to the windows, but at Pennyland a survey found that occupants regarded them as not as good as normal double glazing but better than single glazing. This implies that the problem is acceptable to the occupants.

There were also some difficulties with installing the glass fibre wall batts satisfactorily. In a few cases the end grain of the material was exposed to the outer wall, and mortar build-up on the tops of batts was also noted. These problems stem from a lack of understanding of the water penetration problems and can perhaps be remedied by better site information and training.

The contractor, S + S Homes, currently have moved away from insulation batts, and now post fill the cavities with polystyrene beads. These have a glue coating which consolidates the beads when they are in position. The reason for this decision is that they think that Drytherm batts, such as used at Linford, require too much skill and care to produce a satisfactory result. However, they are also concerned that filling the cavity may increase drying-out times, and they are therefore investigating ways of achieving insulation by using higher insulation blocks and thus avoid filling the cavity.

The retro-fitted door seals were difficult and time consuming to fit. An alternative detail is shown in Figure 4.7, and consists of a silcone tube glued to the frame with silicone mastic. This would have provided a cheaper and more long lasting detail. Another difficulty with doors was experienced with the French doors, which were warped and ill fitting. In low energy houses a more robust locking system which pulls the door in at several points is recommended.

Cold bridging can cause condensation difficulties and forms an increasing percentage of the house heat loss coefficient in low energy houses. Potential cold bridging occurs at three points: through steel combined lintels (Figure 4.6), through the inner wall to ground uninsulated route (Figure 4.3) and through the roof joists (insulation was laid in the normal way between the joists, thus leaving them exposed to cold roof temperatures). Thermographic surveys showed up the cold bridging through lintels and roof, but not through the slab edge, nevertheless this latter detail must still be suspect. To remedy the roof cold bridge, some insulation could be laid across the roof joists, while a different design of lintel could alleviate cold bridging at this point. The cold bridging at the slab edge appears to be of not so much concern. This is perhaps fortunate since no simple low cost solution is known to the authors.

One of the suprises from monitoring was the low ventilation rates achieved with ordinary construction methods. This is discussed in detail in Chapter 8, but it is worth noting that airchange rates in the unoccupied houses was between 0.2 and 0.5 airchanges per hour. These low rates are perhaps due to the integrally draughtstripped windows and the Dacatie cavity closure as well as the balanced fuel boiler which draws its combustion air directly from the outside. Another possible reason is that the complete filling of the cavity reduces ventilation losses through imperfect sealing of the inner leaf of the external wall. One exception to this generally good seal was the ventilation round the stack pipe as it passed through the upper ceiling - careful detailing is needed here.

Finally, it is worth noting that the design briefing procedure worked well, and that the designer found no difficulty in incorporating the measures into the normal house design process.

## 4.4 Conclusions

1. During the design stage, the Energy Brief used was found to work well, and this seemed a good way of briefing the designer. The energy issues seemed to be easily assimilated and incorporated in the design. A further checklist of details e.g., techniques of reducing unwanted ventilation could also be added to this brief.

2. Some of the details were not built as well as possible, and it would be useful to give Clerks of Works and site agents an information sheet of particular points to be checked. This includes information on:

   - Floor insulation positioning prior to pouring the ground floor.
   - Key points in installing cavity insulation batts.
   - Checks on roof insulation installation.

   Generally however, the houses were easily buildable without major snags.

3. The house plans were satisfactory. In elevation, the areas of north face glazing could be reduced by perhaps $1m^2$ and on the south face by $2m^2$ without seriously affecting the overall energy usage. Using door lobbies on one side of the house appeared to work.

4. The problem of scoring on some of the sashless windows needs investigation, although it should be noted that this problem only occured in a serious way on one household, and few if any problems of this nature have been reported on the nearby Pennyland estate, perhaps because it has smaller windows.

5. Cold bridging losses are forming an increasing proportion of the total heat losses, and details required to avoid this problem round wall cavity ties, batt junctions, ceiling joists and inner leaf of external wall to ground junctions.

6. The doors on the south side were a problem. Warping led to an increased air leakage rate. A more secure method of fastening would help to reduce this.

7. Draught sealing was good, but future specification should include draughtstripping of doors.

8. Thermographic tests and ventilation monitoring showed that the houses were thermally well built.

## References

4.1 BRE Note No. 77/81. Buildability of highly insulated masonry houses with enlarged cavities and built in thermal insulation. Hall and Finch, BRE, June 1981.

# 5. ENERGY CONSUMPTION & USE

CONTENTS



This chapter describes the different types of occupancy in the houses and summarises the measured fuel consumptions and resulting fuel costs. Seasonal fuel consumptions are split according to end use, while detailed monthly totals for delivered and useful energy are given in the appendix. An example of an energy balance is constructed for one house.

# 5.0 ENERGY CONSUMPTION AND USE

This chapter summarises the general performance of the Linford occupied houses, in terms of the total annual energy consumption of seven houses, monthly space heating and hot water use for four houses, and a monthly energy balance for one house. Detailed monthly totals for energy use are given in the appendix.

## 5.1 Summary of occupancy

There is a reasonably good spread in occupancy levels and patterns between the seven houses, ranging from an intermittently heated house with two occupants to an almost continuously heated one with four occupants.

Average whole-house temperatures for the period October-April ranged from about 16°C to 20°C. For the lowest case, lounge thermostat settings were generally about 18°C, with bedroom temperatures several degrees cooler. For the highest case, lounge thermostat settings were generally 20-22°C, with all rooms heated much to the same temperature. The other houses lay between these extremes, with lounge thermostat settings of 19-20°C and bedroom temperatures about 2°C cooler.

Table 5.1 gives a summary of occupancy details.

Table 5.1 Summary of occupancy details

| House | No. occupants | | | Heating pattern | | average whole-house temperature Oct-Apr |
|---|---|---|---|---|---|---|
| | adults | children* | total | hrs/day | number of periods | |
| 33 | 4 | 0 | 4 | 18 | 1 | 19.3 |
| 34 | 2 | 2 | 4 | 12 | 2 | not measured |
| 35 | 2 | 2 | 4 | 15 | 1 | 16.2 |
| 36 | 2 | 0 | 2 | 8 | 2 | 18.9 |
| 38 | 2 | 2 | 4 | 18 | 1 | 20.4 |
| 39 | 2 | 2 | 4 | 10 | 2 | 19.2 |
| 40 | 3 | 0 | 3 | 9 | 2 | 19.4 |

*below 16 yrs.

## 5.2 Annual energy consumption

Figure 5.1 and Table 5.2 show annual totals and costs for delivered gas and electricity for seven houses. Breakdowns of the delivered fuel together with

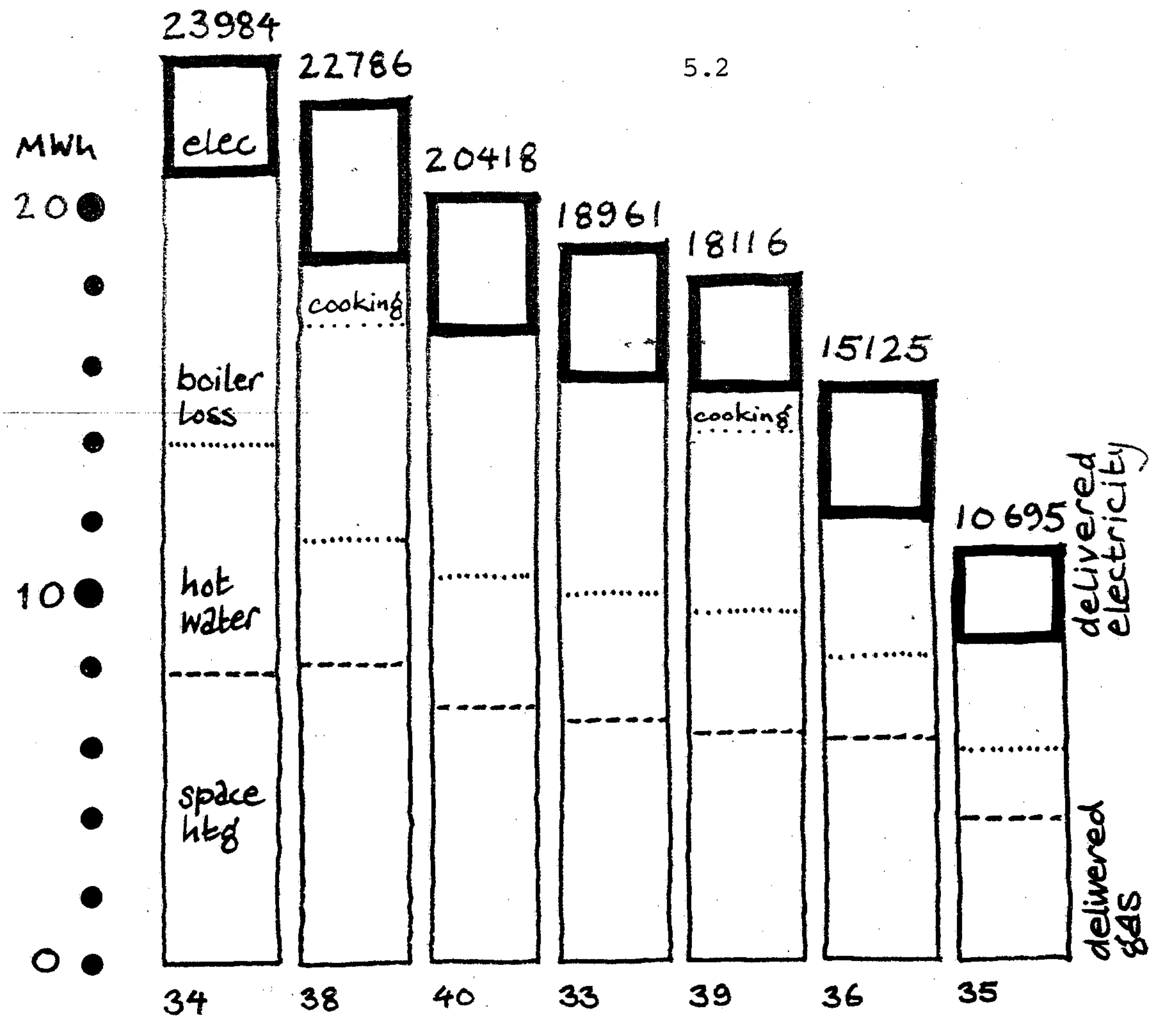



Figure 5.1 Annual fuel consumption of seven Linford houses

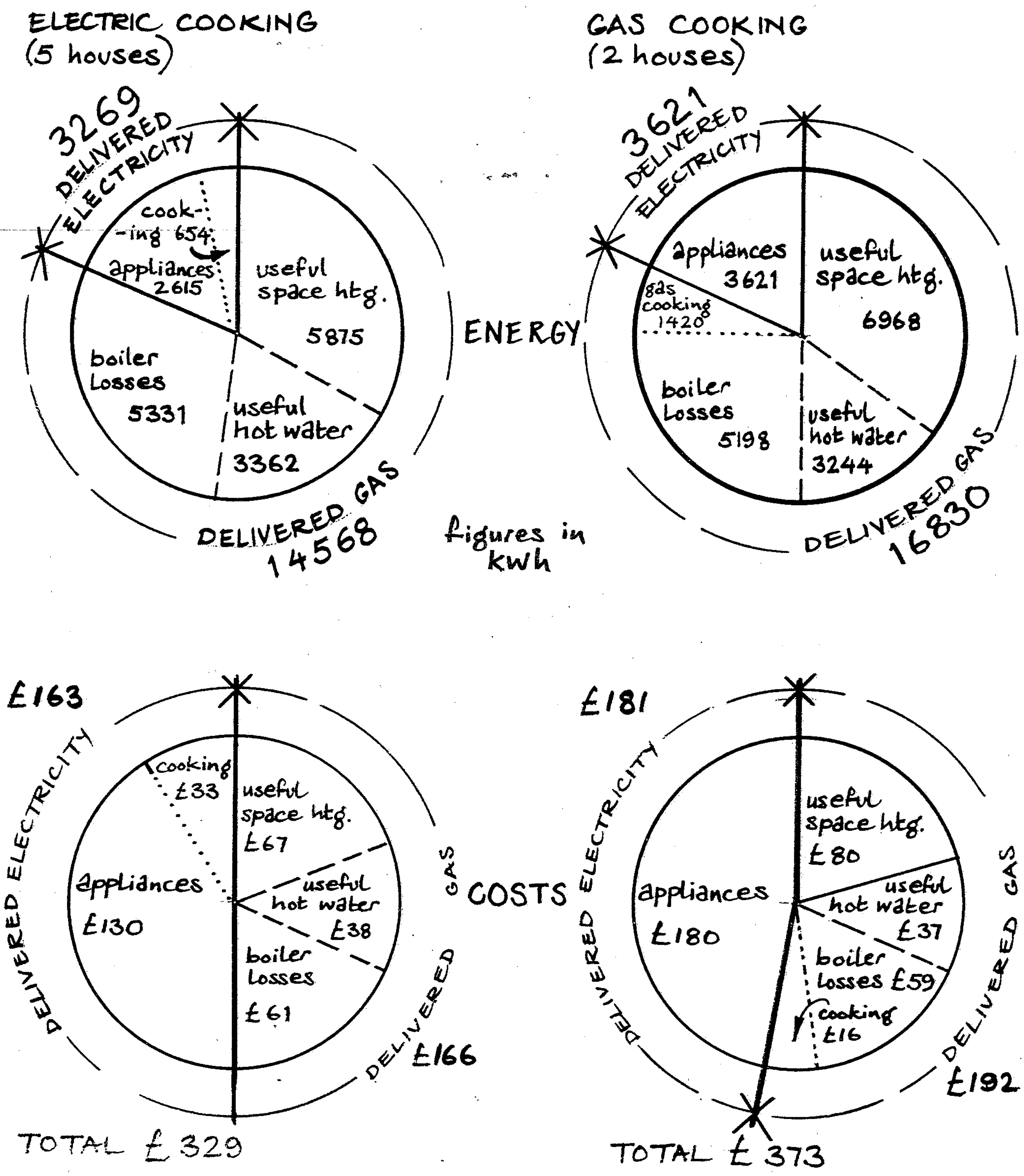



Figure 5.2 Breakdown of delivered fuel: energy and costs (1982)

Table 5.2 Annual fuel consumption and costs (1982)

| HOUSE | DELIVERED FUEL | | | FUEL COSTS* | | |
|---|---|---|---|---|---|---|
| | Gas | Electricity | Total | Gas | Electricity | Total |
| | kWh | kWh | kWh | £ | £ | £ |
| 33 | 15256 | 3705 | 18961 | 174 | 185 | 359 |
| 34 | 20930 | 3054 | 23984 | 239 | 152 | 391 |
| 35 | 8444 | 2251 | 10695 | 96 | 112 | 208 |
| 36 | 11600 | 3525 | 15125 | 132 | 176 | 308 |
| 38 | 18497 | 4289 | 22786 | 210 | 214 | 424 |
| 39 | 15163 | 2953 | 18116 | 173 | 147 | 320 |
| 40 | 16609 | 3809 | 20418 | 189 | 190 | 379 |
| AVERAGE | 15214 | 3369 | 18583 | 173 | 168 | 341 |

Table 5.3 Breakdown of delivered fuel (1982)

| HOUSE | DELIVERED GAS FOR: | | | DELIVERED ELECTRICITY FOR: | | USEFUL HEAT FOR: | | FUEL COSTS* FOR: | |
|---|---|---|---|---|---|---|---|---|---|
| | Space heating + | hot water + | cooking | Appliances | cooking | Space heating | hot water | Space heating | hot water |
| | kWh | kWh | kWh | kWh | kWh | kWh | kWh | £ | £ |
| 33 | 9722 | 5534 | - | 2608 | 1097 | 6379 | 3313 | 110 | 64 |
| 34 | 11288 | 9642 | - | 2354 | 700 | 7722 | 6060 | 129 | 110 |
| 35 | 5175 | 3269 | - | 1805 | 446 | 3622 | 1915 | 59 | 37 |
| 36 | 7982 | 3618 | - | 3018 | 507 | 5777 | 2130 | 91 | 41 |
| 38 | 11281 | 5473 | 1743 | 4289 | - | 7962 | 3206 | 129 | 62 |
| 39 | 8644 | 5426 | 1093 | 2953 | - | 5973 | 3282 | 99 | 62 |
| 40 | 9825 | 6784 | - | 2786 | 1023 | 6784 | 3390 | 112 | 77 |
| AVERAGE | 9137 | 5692 | 1418 | 2830 | 755 | 6317 | 3328 | 104 | 65 |

*Unit costs: Gas 1.14 p/kWh Electricity 4.99 p/kWh
Standing charges excluded

+Including boiler losses

useful heat for space heating and hot water are given in Table 5.3. Figure 5.2 gives the average breakdown for the houses with gas cooking and for those with electric cooking.

The period is January 1982 to December 1982. Gas and electricity totals were calculated from weekly manual readings of the gas and electricity meters. Heat meters were installed in four houses, measuring space heating and hot water consumptions directly. For the remaining three houses, space heating and hot water use were estimated by the following methods:-

(i) For the period June-August, estimate the hot water use from the boiler gas consumption, assuming a boiler efficiency of 44% (average of the four metered houses over this period).

(ii) For the period September-May, estimate the hot water use as 4.6 X the June-August total - this was the average ratio between the two periods, for the four metered houses.

(iii) Estimate the space heating consumption as 68.8% X September-May boiler gas consumption - September to May hot water use. The figure 68.8% is the average boiler efficiency over the space heating period September-May, for the four metered houses.

The following general observations can be made:

1. Even from this small sample of seven houses, there is a considerable range of energy consumptions. The highest is 23984 kWh total delivered energy (gas + electricity), and the lowest is 10695 kWh. This is a spread of 2.2:1. The average total is 18583 kWh. A similar spread exists for space heating requirement - the highest is 7962 kWh, and the lowest is 3622 kWh (2.2:1).

2. Annual fuel costs range from £208 to £424, with an average of £341 (excluding standing charges).

3. Five out of seven houses are paying more for electricity than for gas: the average is about equal.

4. Costs for space heating range from only £59 to £129, with an average of £104. In all cases, the cost of gas for space heating is well below that of electricity.

5. For five out of seven houses, the useful hot water energy is more than half the useful space heating energy; the average is 53%.

Annual fuel costs range from £208 to £424, with an average of £341 (excluding standing charges). Costs for space heating range from only £59 to £129. In all cases the cost of space heating is well below that of electricity consumption.

The low space heating costs suggest significant energy savings due to the low energy design features. However, as there are no control houses, and data for the average fuel requirements of four bedroom houses in the U.K. cannot be found, direct comparisons are not possible.

In chapter 6 estimates are made for the energy savings due to each individual low energy design feature, based on computer modelling supported by various measurements and analyses to be found throughout this report. It concludes that the total delivered energy saving over a Linford house built to 1982 regulations is approximately 10224 kWh. Compared with 1976 regulations the saving is estimated to be 19201 kWh.

These large energy savings, together with points 3 and 5 above perhaps suggest that reductions in non-space heating energy consumption be considered before attempting the next level of space heating energy conservation.

## 5.3 Energy consumption and temperature

Of the various factors that affect energy consumption, the effect of internal temperatures can be clearly demonstrated. For example, the total energy consumption of house 38 is over twice that of house 35 (22786 kWh c.f 10695 kWh), yet the number of occupants is the same in each case - two adults and two small children. While some of this difference is due to higher uses of electricity and hot water in house 38 (Table 5.3), most of the difference results from higher internal temperatures during the space heating season - 20.4°C (Oct-Apr) compared with 16.2°C.

A strong correlation is seen between space heating consumption and October-April average whole-house internal temperatures (below, and Figure 5.3).

| House | Av. House temp. °C | useful space heating kWh |
|---|---|---|
| 35 | 16.2 | 3622 |
| 36 | 18.9 | 5777 |
| 39 | 19.2 | 5973 |
| 33 | 19.3 | 6379 |
| 40 | 19.4 | 6784 |
| 38 | 20.4 | 7962 |
| Average | 18.9 | 6082 |

Considering that there are several other factors that affect space heating demand other than temperature (e.g. incidental gains, ventilation rate, solar gains), such a relationship is over-simplified, and the high degree of correlation is perhaps fortuitous (more detailed analysis can be found in chapters 8 and 10). However, the crude data clearly shows large differences in energy consumption and hence cost, attributable to differences in internal temperatures. For every 1°C increase in average internal temperatures, the space heating requirement increases by approximately 1000 kWh. This requires about 1500 kWh delivered gas, costing £17 per year. In the case of house 35, this represents nearly a 25% increase in space heating costs (including standing charge). For house 38, a reduction of 1°C would represent a 12% reduction in space heating costs.

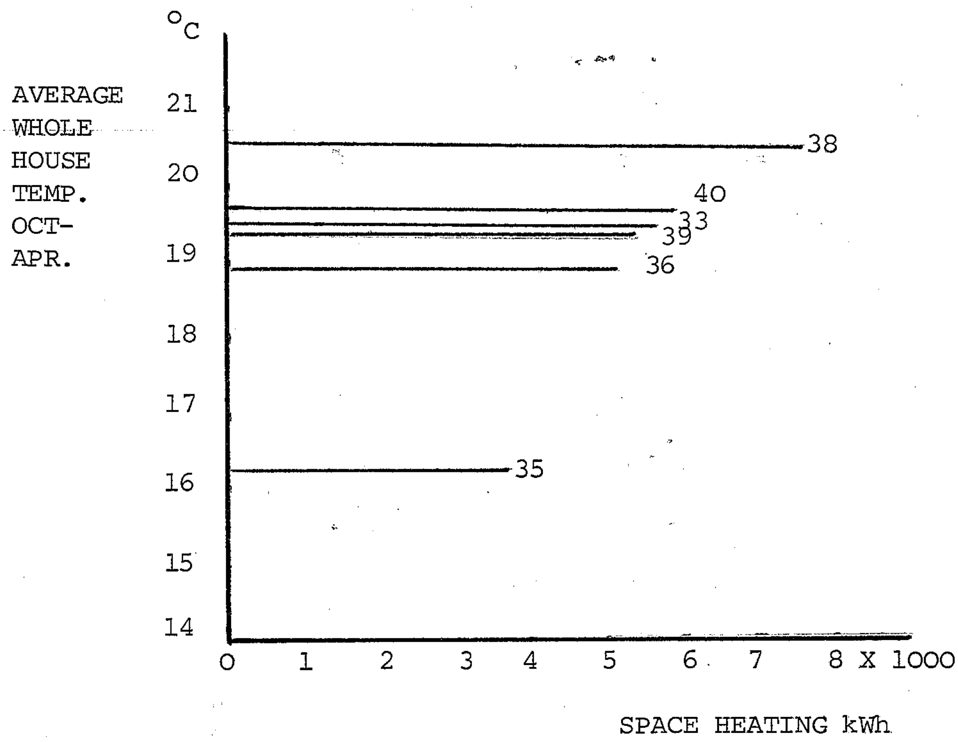



Figure 5.3 A wide range of preferred temperatures produces considerable variation in space heating requirement

## 5.4 Seasonal variation

### 5.4.1 Gas and electricity

In addition to hourly data recorded on the data loggers, weekly meter readings were taken for total gas and electricity consumptions. This data is plotted for all seven houses in the appendix, and two such plots are reproduced in Figure 5.4. The two houses shown represent the full range of fuel consumption for the seven houses, the data covering the period January 1st 1981 to May 31st 1983. Again, the ratios are approximately 2:1.

### 5.4.2 Space heating and hot water

Figure 5.5 shows monthly space heating consumptions, and inside and outside air temperatures, for two houses over two heating seasons. These are for the highest and lowest, again houses 38 and 35. The ratio between the two houses is approximately 2:1, due mainly to the different internal temperatures.

The 1981/82 winter is generally regarded as one of the worst since 1963. However, the particularly cold spell only lasted about 2 months, and there are only small differences between total space heating consumptions for the two periods.

The length of the heating season can be seen in Figure 5.5. For house 35, it is October to April, but for house 38 there is still a significant heat demand in May.

Figure 5.6 shows examples of hot water use. For some reason, house 34 appears to have an exceptionally high hot water use of over 6000 kWh/yr (Table 5.2). However, this is the least monitored house with only weekly gas and electricity data available. For house 33, the next highest consumers, there is measured data for hot water use and this is compared with the lowest user, house 35. The annual totals are 3313 kWh and 1915 kWh. The difference is presumably due to the higher number of occupants in house 33 - four adults compared with two adults and a small child. Note the strong seasonality for house 33.

## 5.5 Energy balance and solar gains

Chapter 12 deals in detail with energy balances for four houses. One example is reproduced here, that for house 36 for 1982/83, in Figure 5.7.

Curve 1 is the total heat requirement (including solar gains) necessary to maintain the actual temperatures that were recorded, based on best estimates for the fabric, floor and ventilation heat loss characteristics derived in chapters 8 and 10. Curve 2 is the estimated incidental gains, based on the assumptions explained in chapter 11. Curve 3 is the result of deducting the measured space heating from curve 1, the total heat requirement. Thus the area bounded by the y-axes and curves 3 and 2 represents the total solar heat input to the house, useful or not. Curve 4 represents the expected version of curve 1, if the internal temperature had stayed at the wintertime whole-house temperature level of about 19°C, as set by the living room and bedroom thermostats, instead of rising above this due to excess solar gains. Thus the shaded area is an estimate of the useful solar gains.

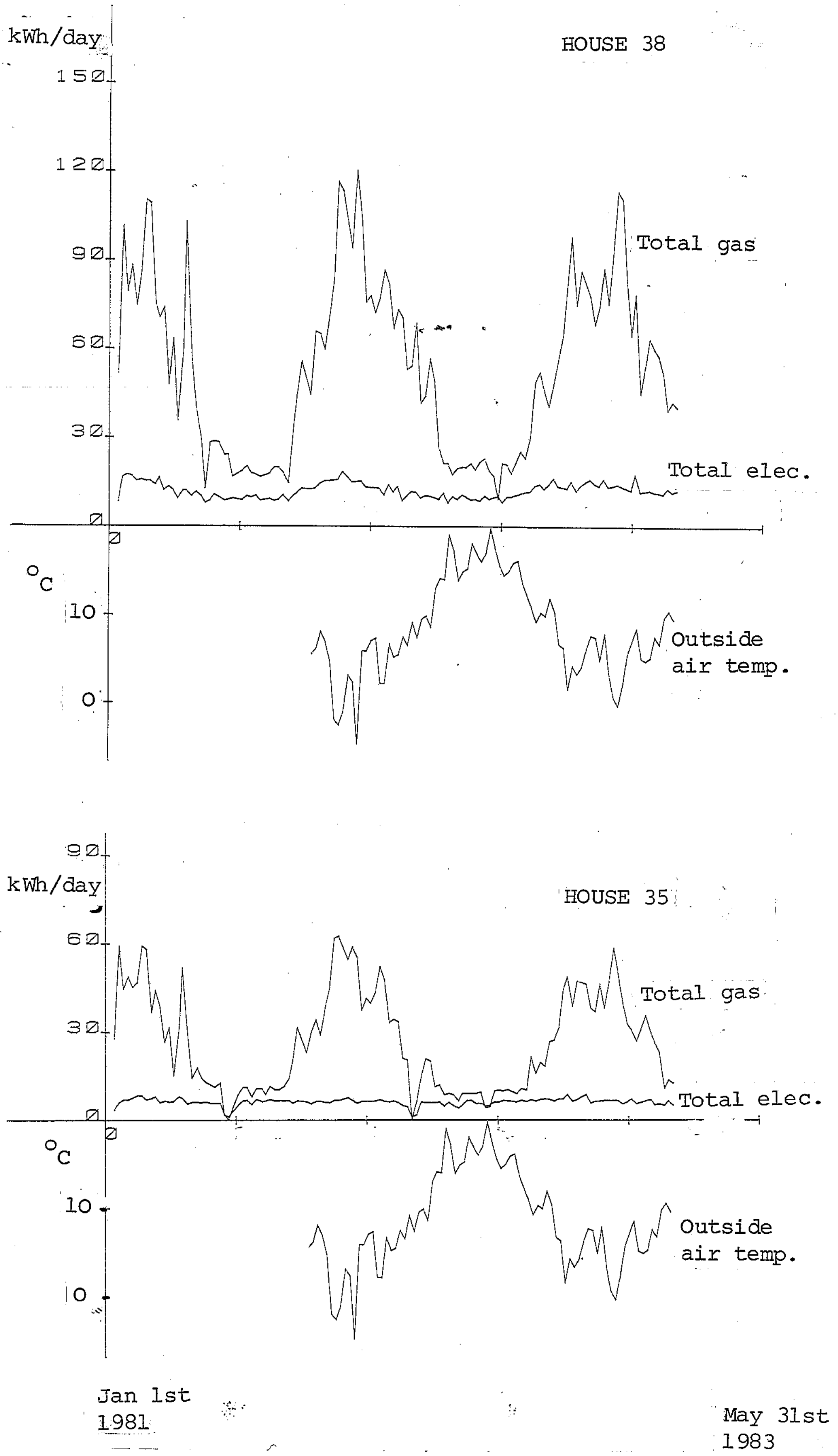
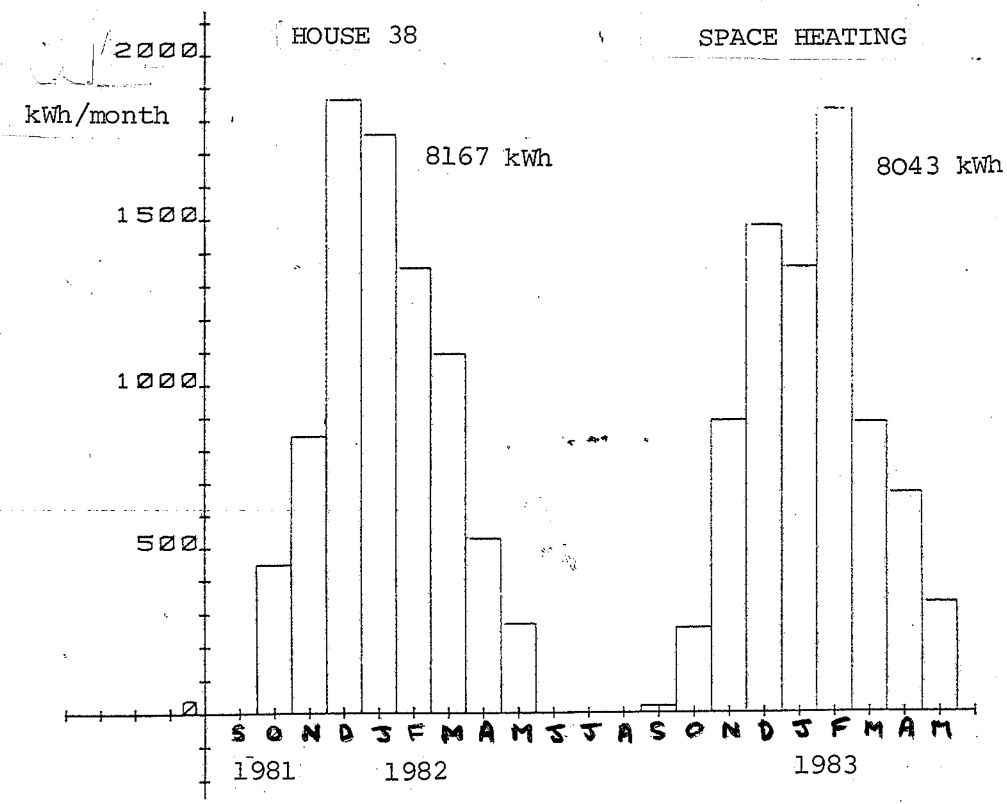
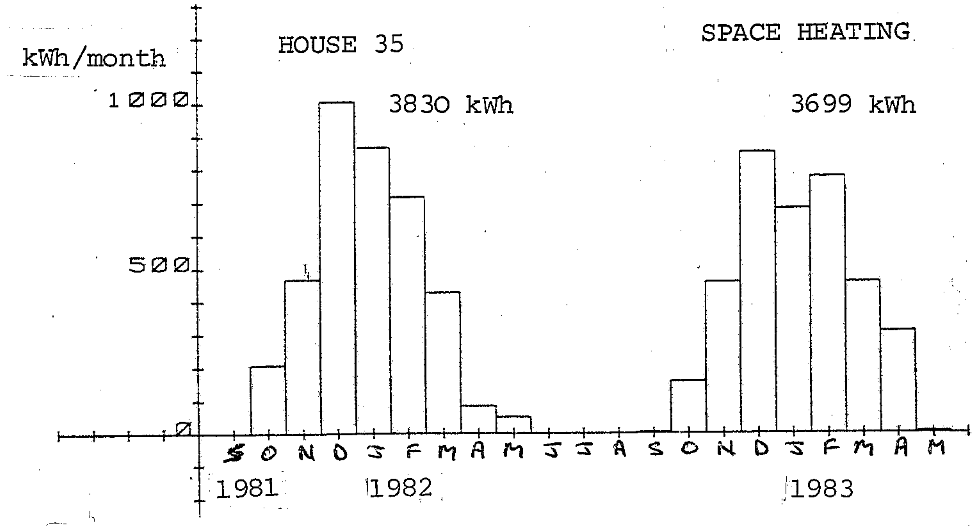



Figure 5.4 Weekly average gas and electricity consumption for two houses (approx. highest and lowest-range is about 2:1)



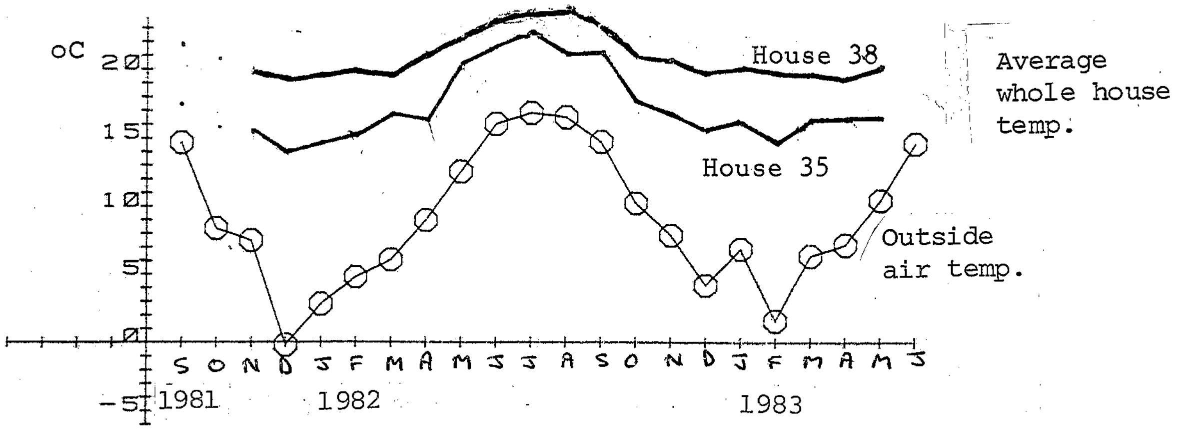
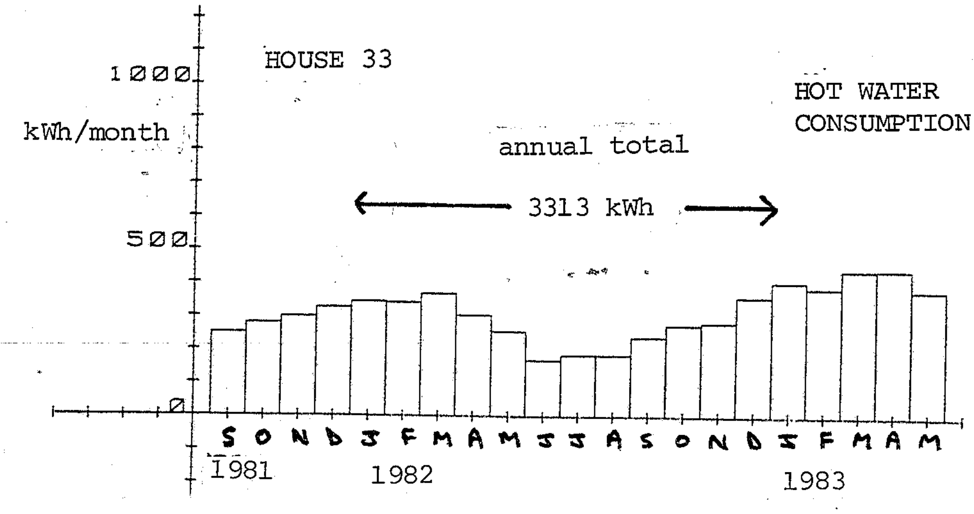




Figure 5.5 Monthly space heating consumption of two houses (highest and lowest - range approx. 2:1)



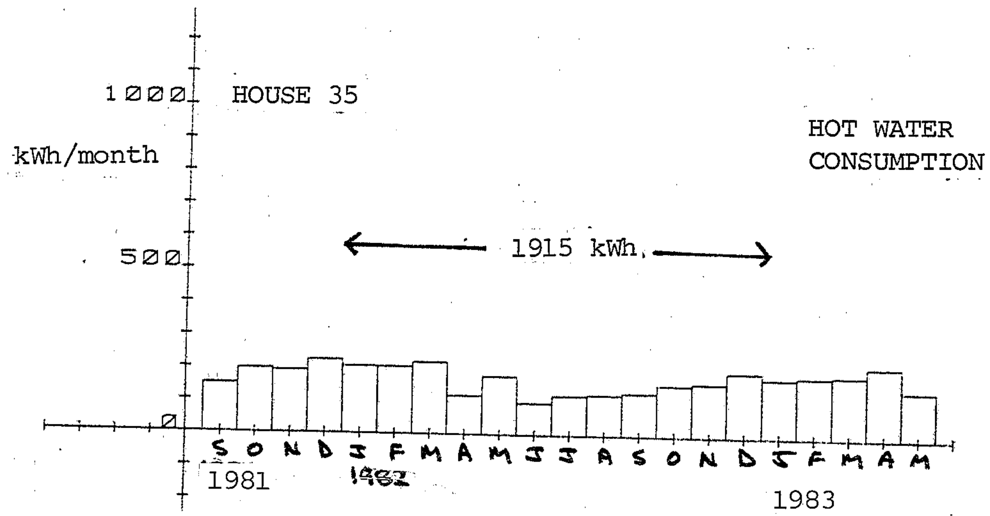




Figure 5.6 Monthly hot water consumption for two houses (note the stong seasonal variation for No 33)

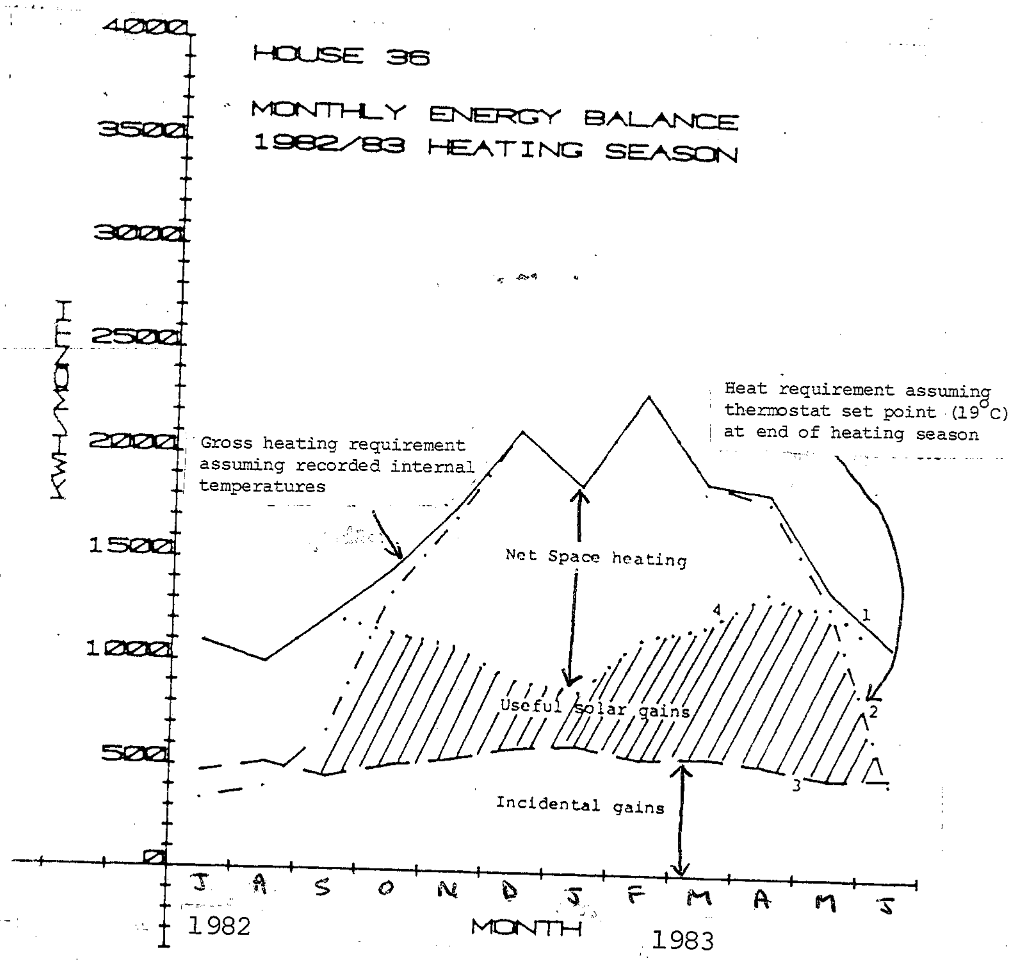



Figure 5.7 Energy balance for house 36

The useful heat inputs to the heated space for September to May for this house were:

| | | |
|---|---|---|
| Incidental gains | 4870 kWh | 32% |
| Useful solar gains | 4484 kWh | 30% |
| Net space heating | 5654 kWh | 38% |

The averages for four houses were:

| | | |
|---|---|---|
| Incidental gains | 5771 kWh | 38% |
| Useful solar gains | 3573 kWh | 24% |
| Net space heating | 5748 kWh | 38% |

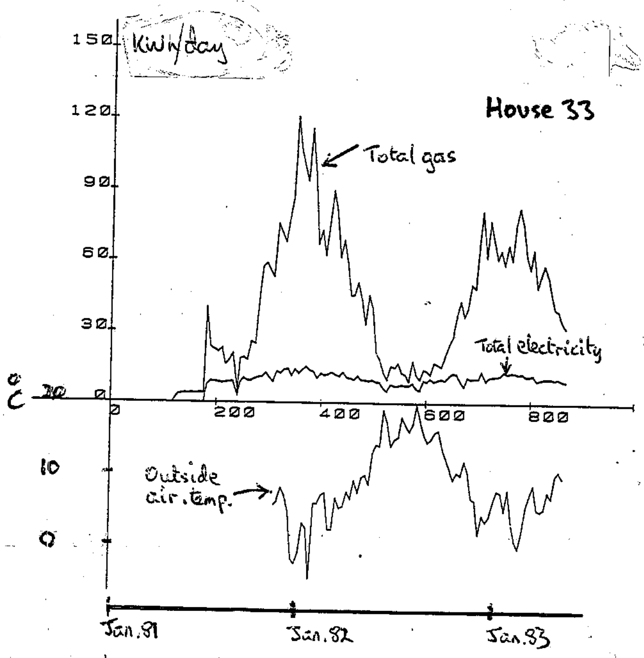
These figures show that solar gains make up a significant part of the total useful heat input to the heated space. However, absolute solar gains are not particularly useful is assessing the success of passive solar design and its cost-effectiveness, as <u>all</u> houses, passive solar or not, make some use of solar gains. For this purpose, <u>marginal</u> solar gains must be considered. i.e. the difference in useful solar gain between the Linford "passive" design and a "normal" equivalent, which in itself can be difficult to define. Chapter 10 deals with this in some detail.

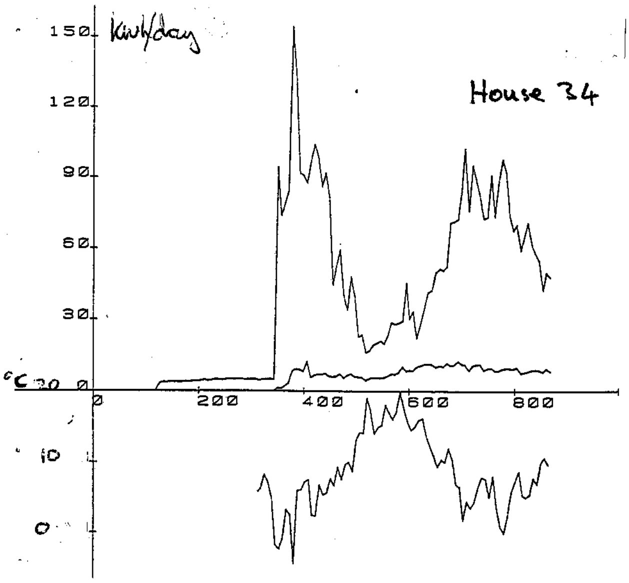
## Appendix

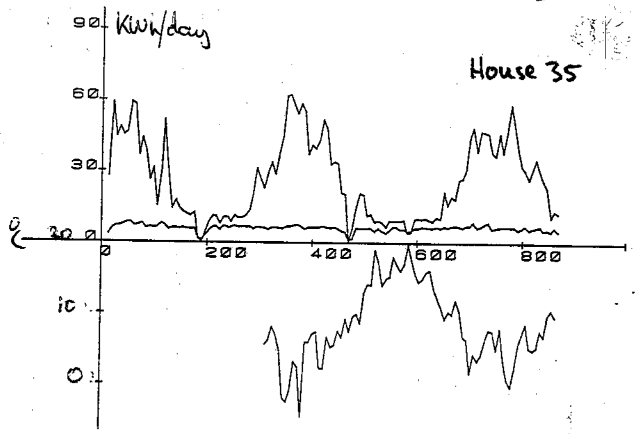
Figure A5.1 shows weekly gas and electricity consumptions for all seven occupied houses. This is effectively a data map, showing periods of occupancy for each house.

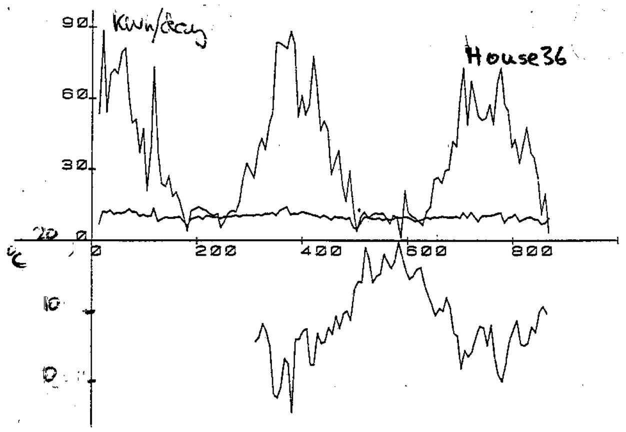
Tables A5.1-A5.4 give monthly data for gas and electricity consumption, space heating and hot water use, boiler efficiency, and inside and outside temperatures in four houses. The inside temperature is the whole-house average as defined in Chapter 14.

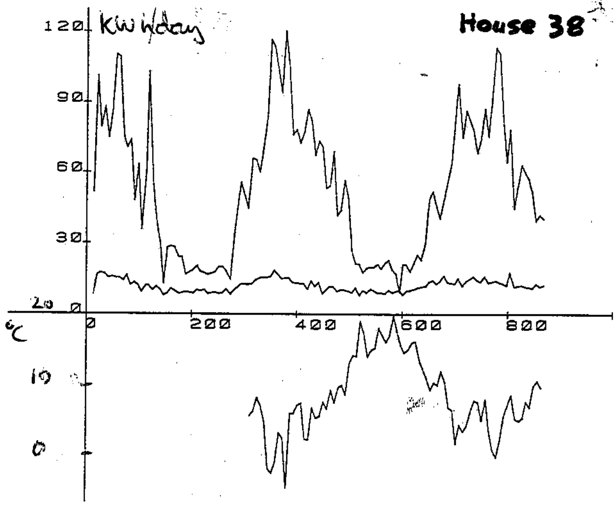
The space heating and hot water data are plotted in Figure A5.2.

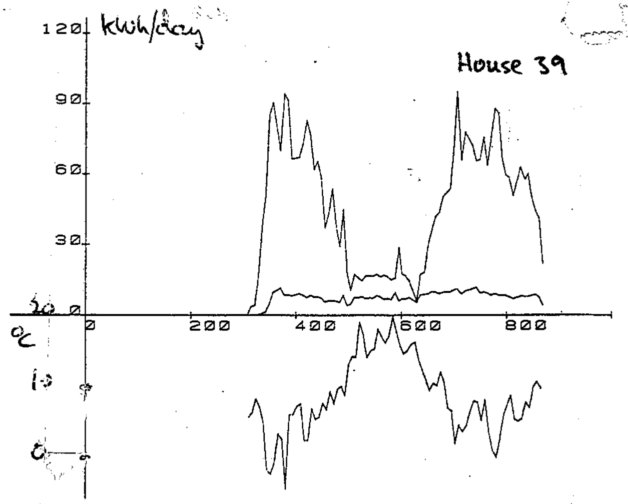


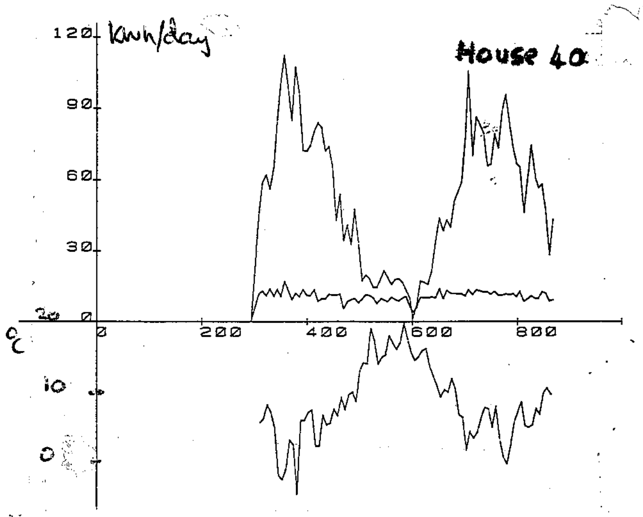




Figure A5.1 Total gas and electricity consumptions - weekly averages

Day 1 = Jan 1st 1981
Day 881=May 31st 1983

Figure A5.2

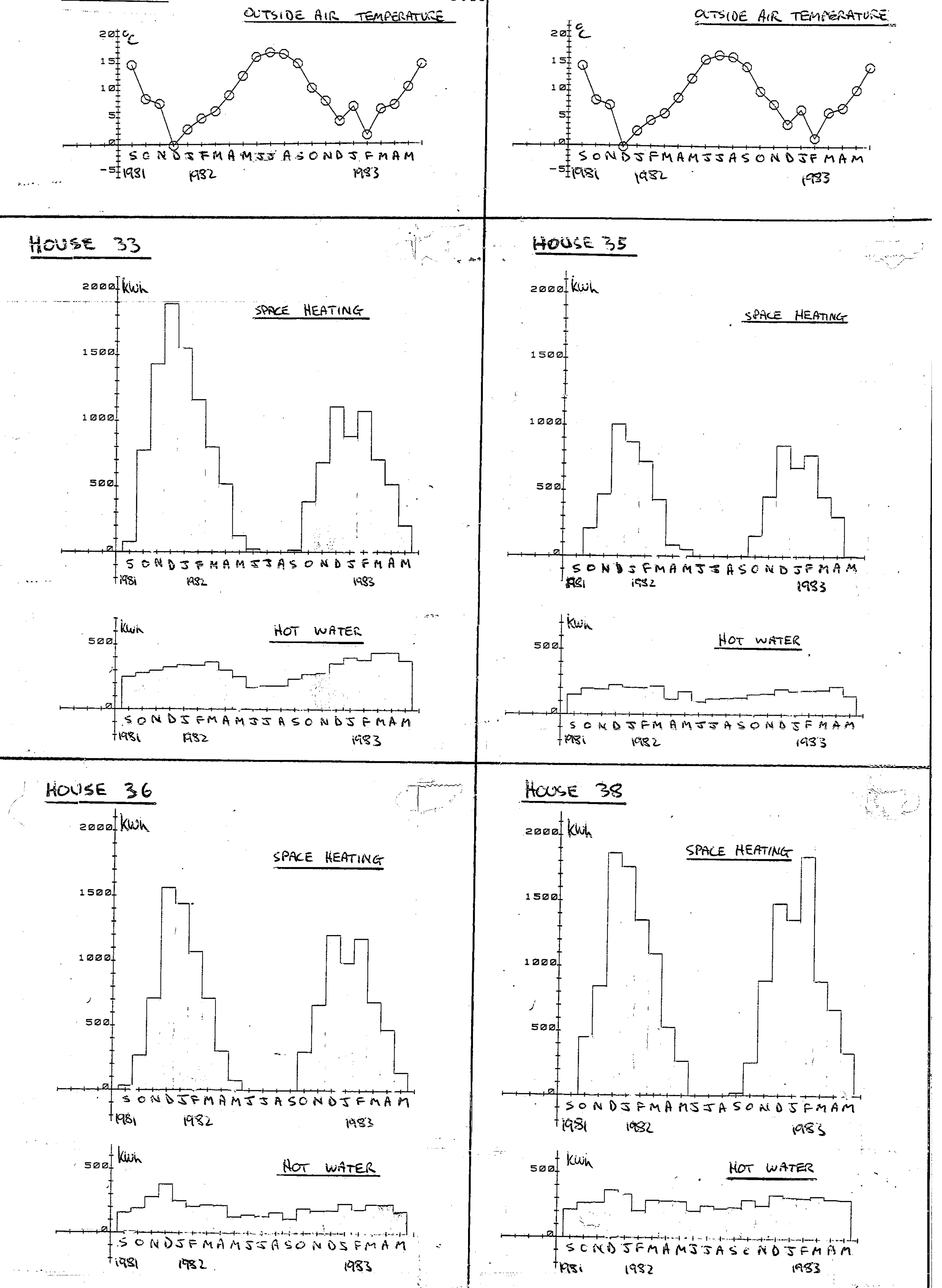

OUTSIDE AIR TEMPERATURE
°C
20
15
10
5
0
-5
S O N D J F M A M J J A S O N D J F M A M
1981
1982
1983
HOUSE 33
HOUSE 35
HOUSE 36
HOUSE 38
SPACE HEATING
HOT WATER
kWh
2000
1500
1000
500
0

Table A5.1 Monthly data for house 33
figures in brackets denote estimates

| Month | Gas | Electricity | | | Space heating | | | Hot water | Boiler eff. | Temperatures | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | cooker | appl. | total | down | up | total | | | inside | outside |
| | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | % | °C | °C |
| Sep 81 | 655 | 90 | 204 | 294 | | | (78) | (250) | (50) | | |
| Oct | 1621 | 85 | 243 | 328 | | | (774) | (280) | (65) | | |
| Nov | 2543 | 89 | 304 | 393 | 1081 | (349) | (1430) | 299 | (68) | | |
| Dec | 3167 | 103 | 326 | 429 | 1391 | (499) | (1890) | 326 | (70) | 20.3 | 7.5 |
| Jan 82 | 2707 | 99 | 298 | 397 | 1246 | (305) | (1551) | 344 | (70) | 19.8 | -0.2 |
| Feb | 2206 | 102 | 243 | 345 | 949 | (210) | (1159) | 341 | (68) | 19.6 | 2.8 |
| Mar | 1798 | 104 | 245 | 349 | 704 | (97) | (801) | 368 | (65) | 19.4 | 4.8 |
| Apr | 1308 | 111 | 201 | 312 | 456 | (64) | (520) | 304 | (63) | 19.4 | 6.1 |
| May | 837 | 89 | 188 | 274 | 192 | 34 | 226 | 256 | 57.5 | 19.8 | 9.0 |
| Jun | 424 | 57 | 149 | 206 | 24 | 0 | 24 | 170 | 45.8 | 21.3 | 12.6 |
| Jul | 390 | 76 | 156 | 232 | 0 | 0 | 0 | 185 | 45.9 | 22.4 | 16.1 |
| Aug | 403 | 79 | 189 | 268 | 0 | 0 | 0 | 185 | 45.9 | 22.6 | 16.9 |
| Sep | 510 | 91 | 200 | 291 | 16 | 0 | 16 | 239 | 50.0 | 21.9 | 16.6 |
| Oct | 1054 | 92 | 249 | 341 | 355 | 32 | 387 | 276 | 62.9 | 21.9 | 14.8 |
| Nov | 1489 | 91 | 217 | 308 | 626 | 59 | 685 | 284 | 65.1 | 19.7 | 10.3 |
| Dec | 2130 | 106 | 276 | 382 | 952 | 158 | 1110 | 361 | 69.1 | 19.2 | 7.9 |
| Jan 83 | 1899 | 124 | 258 | 382 | 813 | 73 | 886 | 406 | 68.0 | 18.2 | 4.2 |
| Feb | 2094 | 117 | 233 | 350 | 906 | 170 | 1076 | 388 | 69.9 | 18.7 | 6.9 |
| Mar | 1768 | 107 | 227 | 334 | 618 | 91 | 709 | 444 | 65.2 | 17.8 | 1.6 |
| Apr | 1450 | 103 | 214 | 317 | 466 | 54 | 520 | 446 | 66.6 | 18.9 | 6.4 |
| May | 938 | 102 | 198 | 300 | 206 | 0 | 206 | 383 | 62.7 | 19.1 | 7.2 |

Table A5.2 Monthly data for house 35

| Month | Gas | Electricity | | | Space heating | Hot water | Boiler eff. | Temperatures | |
|---|---|---|---|---|---|---|---|---|---|
| | | cooker | appl. | total | | | | inside | outside |
| | kWh | kWh | kWh | kWh | kWh | kWh | % | °C | °C |
| Sep 81 | 246 | | | 203 | (0) | (150) | 61.0 | (17.5) | 14.7 |
| Oct | 685 | | | 198 | (207) | (197) | 58.9 | (16.0) | 8.4 |
| Nov | 936 | 35 | 142 | 177 | 468 | 192 | 70.5 | 15.8 | 7.5 |
| Dec | 1770 | 50 | 163 | 213 | 1005 | 225 | 69.5 | 14.0 | -0.2 |
| Jan 82 | 1474 | 43 | 164 | 207 | 868 | 206 | 72.9 | 14.8 | 2.8 |
| Feb | 1235 | 42 | 143 | 185 | 719 | 205 | 74.8 | 15.4 | 4.8 |
| Mar | 959 | 45 | 145 | 190 | 429 | 219 | 67.6 | 16.8 | 6.1 |
| Apr | 327 | 20 | 83 | 103 | 84 | 118 | 61.8 | 16.3 | 9.0 |
| May | 454 | 30 | 152 | 182 | 50 | 177 | 50.0 | 20.3 | 12.6 |
| Jun | 254 | 20 | 136 | 156 | 0 | 97 | 38.2 | 21.7 | 16.1 |
| Jul | 264 | 38 | 152 | 190 | 0 | 121 | 45.8 | 22.6 | 16.9 |
| Aug | 262 | 35 | 155 | 190 | 0 | 125 | 47.7 | 21.4 | 16.6 |
| Sep | 291 | 40 | 156 | 196 | 4 | 131 | 46.4 | 21.3 | 14.8 |
| Oct | 537 | 47 | 180 | 227 | 158 | 156 | 58.5 | 17.9 | 10.3 |
| Nov | 935 | 43 | 153 | 196 | 458 | 163 | 66.4 | 16.9 | 7.9 |
| Dec | 1452 | 43 | 186 | 229 | 852 | 197 | 72.2 | 15.6 | 4.2 |
| Jan 83 | 1234 | 23 | 192 | 207 | 681 | 180 | 69.8 | 16.1 | 6.9 |
| Feb | 1371 | 18 | 165 | 190 | 776 | 186 | 70.2 | 14.7 | 1.6 |
| Mar | 959 | 22 | 143 | 200 | 458 | 190 | 67.6 | 16.2 | 6.4 |
| Apr | 810 | 25 | 207 | 178 | 307 | 218 | 64.8 | 16.6 | 7.2 |
| May | 307 | 29 | 226 | 155 | 5 | 147 | 49.5 | 16.5 | 10.5 |

Table A5.3 Monthly data for house 36

| Month | Gas | Electricity | | | Space heating | Hot water | Boiler eff. | Temperatures | |
|---|---|---|---|---|---|---|---|---|---|
| | | cooker | appl. | total | | | | inside | outside |
| | kWh | kWh | kWh | kWh | kWh | kWh | % | °C | °C |
| Sep 81 | 318 | 53 | 250 | 303 | (33) | (158) | 60.1 | (20.7) | 14.7 |
| Oct | 778 | 52 | 272 | 324 | (268) | (192) | 59.1 | (19.4) | 8.4 |
| Nov | 1227 | 52 | 274 | 326 | 711 | 281 | 80.8 | 18.2 | 7.5 |
| Dec | 2338 | 63 | 317 | 380 | 1561 | 381 | 83.1 | 17.5 | -0.2 |
| Jan 82 | 2210 | 69 | 299 | 368 | 1439 | 252 | 76.5 | 18.7 | 2.8 |
| Feb | 1766 | 52 | 262 | 314 | 1073 | 209 | 72.6 | 18.8 | 4.8 |
| Mar | 1328 | 44 | 260 | 304 | 713 | 221 | 70.3 | 19.1 | 6.1 |
| Apr | 813 | 46 | 241 | 287 | 302 | 217 | 63.8 | 19.5 | 9.0 |
| May | 406 | 23 | 201 | 224 | (75) | 128 | (50.0) | 21.4 | 12.6 |
| Jun | 350 | 40 | 254 | 294 | 0 | 143 | 40.8 | 23.1 | 16.1 |
| Jul | 293 | 37 | 237 | 274 | 0 | 132 | 45.1 | 23.7 | 16.9 |
| Aug | 363 | 43 | 265 | 308 | 0 | 163 | 44.9 | 22.6 | 16.6 |
| Sep | 260 | 36 | 227 | 263 | 0 | 113 | 43.5 | 22.4 | 14.8 |
| Oct | 744 | 40 | 238 | 278 | 301 | 194 | 66.5 | 19.7 | 10.3 |
| Nov | 1239 | 41 | 252 | 293 | 669 | 178 | 68.4 | 19.3 | 7.9 |
| Dec | 1828 | 36 | 281 | 317 | 1205 | 180 | 75.8 | 17.5 | 4.2 |
| Jan 83 | 1645 | 52 | 276 | 328 | 991 | 233 | 74.4 | 18.4 | 6.9 |
| Feb | 1817 | 41 | 244 | 285 | 1178 | 187 | 75.1 | 17.2 | 1.6 |
| Mar | 1273 | 47 | 257 | 304 | 691 | 228 | 72.2 | 18.5 | 6.4 |
| Apr | 1035 | 33 | 238 | 271 | 476 | 229 | 68.1 | 19.3 | 7.2 |
| May | 557 | 43 | 197 | 240 | 143 | 173 | 56.7 | 19.5 | 10.5 |

Table A5.4 Monthly data for house 38

| Month | Gas | | | Electricity | Space heating | Hot water | Boiler eff. | Temperatures | |
|---|---|---|---|---|---|---|---|---|---|
| | cooker | boiler | total | | | | | inside | outside |
| | kWh | kWh | kWh | kWh | kWh | kWh | % | °C | °C |
| Sep 81 | 121 | 428 | 549 | 283 | (0) | (214) | (50) | (22) | 14.7 |
| Oct | 149 | 1191 | 1340 | 355 | (450) | (265) | (60) | (21) | 8.4 |
| Nov | 138 | 1744 | 1882 | 429 | 845 | 268 | 63.8 | 20.2 | 7.5 |
| Dec | 171 | 2914 | 3085 | 504 | 1866 | 365 | 76.6 | 19.5 | -0.2 |
| Jan 82 | 171 | 2812 | 2983 | 452 | 1760 | 335 | 74.5 | 19.9 | 2.8 |
| Feb | 123 | 2099 | 2222 | 354 | 1354 | 208 | 74.4 | 20.0 | 4.8 |
| Mar | 144 | 2009 | 2153 | 365 | 1095 | 289 | 68.9 | 19.8 | 6.1 |
| Apr | 163 | 1359 | 1522 | 314 | 529 | 285 | 59.9 | 21.2 | 9.0 |
| May | 156 | 867 | 1023 | 301 | 268 | 279 | 59.8 | 21.9 | 12.6 |
| Jun | 156 | 672 | 828 | 310 | 0 | 209 | 31.1 | 23.4 | 16.1 |
| Jul | 161 | 524 | 685 | 280 | 0 | 248 | 47.3 | 23.6 | 16.9 |
| Aug | 126 | 428 | 554 | 307 | 0 | 229 | 53.5 | 24.1 | 16.6 |
| Sep | 137 | 549 | 686 | 324 | 20 | 238 | 47.0 | 22.8 | 14.8 |
| Oct | 145 | 1263 | 1408 | 415 | 564 | 295 | 68.0 | 21.1 | 10.3 |
| Nov | 131 | 1685 | 1816 | 423 | 891 | 255 | 68.0 | 20.6 | 7.9 |
| Dec | 130 | 2487 | 2617 | 444 | 1481 | 336 | 73.1 | 19.9 | 4.2 |
| Jan 83 | 137 | 2205 | 2342 | 458 | 1357 | 318 | 76.0 | 20.1 | 6.9 |
| Feb | 124 | 2675 | 2799 | 383 | 1842 | 314 | 80.6 | 19.9 | 1.6 |
| Mar | 144 | 1785 | 1929 | 409 | (885) | 329 | (68) | 19.9 | 6.4 |
| Apr | 133 | 1505 | 1638 | 351 | (671) | 307 | (65) | 19.4 | 7.2 |
| May | 140 | 1058 | 1198 | 382 | (332) | 303 | (60) | 20.2 | 10.5 |

# 6. ENERGY SAVINGS

CONTENTS



Much of the detailed performance results that appear throughout this report are brought together in this chapter, to estimate the savings that can be attributed to individual energy-saving features. As there were no control houses built in the project, this has been done by computer modelling.

# 6. ENERGY SAVINGS

## 6.1 Introduction

The Linford houses have been designed to incorporate a number of energy saving features, insulation, a high level of passive solar gains, a low air change rate and a high efficiency low thermal capacity boiler.

Although the project has shown that the houses have a low overall energy consumption, the energy savings cannot be demonstrated directly since there are no control houses. The project energy savings have thus been calculated using the NBSLD-based model used in the design process (Reference 6.1). This has been adjusted as far as possible to correspond to the actual measured house performance using data from various experimental tests.

This model of an "average" Linford house has been compared with a model of a "normal" house in order to assess the energy savings due to insulation and passive solar measures.

Since this process may lack a certain amount of credibility, a similar calculation process for the companion Pennyland project is given at the end of this chapter. Here calculated energy savings can be compared directly with large demonstrated savings. The Pennyland project shows large energy savings by comparing groups of houses at different insulation levels, but the level of monitoring has not allowed the detailed energy analysis of this project.

### 6.1.1 The reference house

The energy savings have been calculated in a stepwise manner for Linford, starting from a 'reference house' shell built to 1982 Building Regulation insulation standards (the same shell built to 1976 standards has been included for comparison). This reference house is as far as possible an estimate of what would have been built in place of the Linford houses in 1982. It would have had the 1982 insulation level, an indifferent boiler and not much thought about house orientation, overshading or airtightness.

Defining 'normalcy' for a reference house is a little difficult. For airtightness and boiler efficiency the Neath Hill estate houses, built in 1978, have been used as examples, together with an airtightness survey of a variety of reasonably modern UK houses, as measured by the BRE (Reference 6.2). Overshading and orientation considerations have been drawn from a survey of the Cambridge housing stock made by the Martin Centre (Reference 6.3).

The reference house has been taken to be a normal dual aspect house of the same size as the Linford houses. Unfortunately the 1982 Building Regulations would not permit the large glazing area of the Linford houses without some extra insulation being added. In order to keep matters simple, the reference house has been taken to have the same total window area as the Linford houses, but all but 7 $m^2$ of this area is assumed to be double glazed.

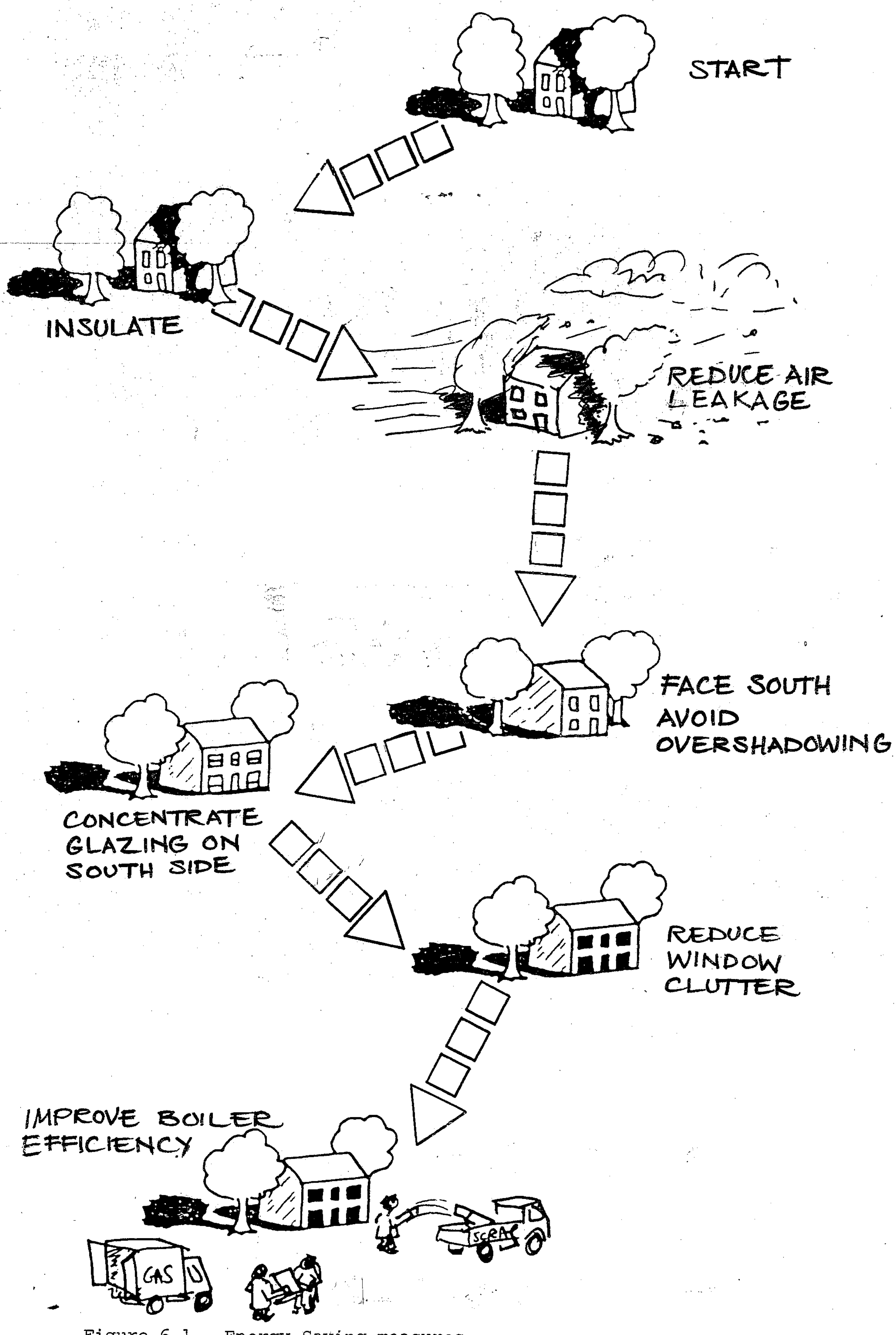



Figure 6.1 Energy Saving measures

Other basic details are given below:-

REFERENCE HOUSE SHELL

| | | | | |
|---|---|---|---|---|
| S.W. Facing | Net Curtains | Normally overshaded | | |
| Window Areas | N.E. | $13.8m^2$ | $20.6m^2$ | double glazed |
| | S.W. | $13.8m^2$ | $7\ m^2$ | single glazed |
| Wall Area | | $131.7\ m^2$ | | |
| Roof/Floor Area | | $55\ m^2$ | | |
| Door Area | | $3.6\ m^2$ | | |
| Free Heat Gains | | 21.7 kWhr/day | | |
| Whole House Thermostat Setting | | $20^{\circ}$ C | | |
| Heating Period | | 16 hrs/day | | |
| Weather Data | | Kew 1969 | | |

The energy savings have been calculated in a stepwise manner, as illustrated in Figure 6.1, first insulation, then reducing air leakage, marginal passive solar gains due to correct orientation, avoiding overshading, concentrating glazing on the south side and minimising window clutter, and finally improving boiler efficiency.

The reference house design has been carefully costed and the calculated energy savings and costs are brought together in the next chapter to give the general cost-effectiveness.

## 6.2 Insulation savings

The model has been used to calculate annual space heating consumptions for different insulation levels for the same house shell, using the same assumptions about occupancy and thermostat settings, as outlined above.

For simplicity of calculation and comparison, observed defects such as the high floor U-value measured in the Linford test house has also been incorporated into the reference house, allowing the end of the chain of calculations to approximate as closely as possible to the actual houses as built. A small fixed allowance has been included for lintel and joist cold bridging, which is likely to be independent of the actual insulation level. Otherwise the thermal performance of the insulation measures has proceeded without allowance for cold bridging.

The K-value of glass fibre insulation has been taken as 0.033 W/m $^{\circ}$C since this agrees fairly well with the measurements in Chapter 8.

The energy savings due to particular measures are to a certain extent dependent on the order in which they are calculated. Adding more

Table 6.1 Reference House Insulation and Air Leakage Savings

| | Total Heat Loss $W/^{\circ}C$ | Annual Space Heating kWh/yr | Energy Saving kWh/yr |
|---|---|---|---|
| 1976 Building Regulations<br><br>Unfilled cavity walls<br>50 mm roof insulation<br>Single glazing<br>Floor U-value 1.1 $W/^{\circ}C$<br>Air change rate 0.6 ac/h | 405 | 16609 | - |
| Roof insulation 50 mm - 100 mm | 391 | 15901 | 708 |
| Wall insulation 50 mm added | 323 | 11829 | 4072 |
| 20.6 $m^2$ double glazing -<br><br>1982 Building Regulations<br><br>50 mm cavity wall insulation<br>100 mm roof insulation<br>20.6 $m^2$ double glazing<br>7 $m^2$ single glazing<br>Floor U-value 1.1 $W/^{\circ}C$<br>Air change rate 0.6 ac/hr | 286 | 10572 | 1257 |
| Roof insulation 100 mm - 150 mm | 280 | 10236 | 336 |
| Full double glazing | 268 | 9689 | 547 |
| Wall insulation 50 mm - 100 mm | 244 | 8133 | 1556 |
| Floor edge insulation<br>U-value 1.1 $W/^{\circ}C$ - 0.9 $W/^{\circ}C$ | 233 | 7581 | 552 |
| Reduce air change rate to 0.38 ac/hr | 213 | 6344 | 1237 |

insulation to a poorly insulated house has a larger effect than adding the same amount to a well insulated one. The measures have thus been calculated in the order in which they are most likely to be put into practice, but this is largely arbitrary.

Since it appears that the Linford houses have a floor U-value of about 0.9 $W/m^2\ ^oC$ despite having slab edge insulation (see Chapter 8), the U-value of a floor with no slab edge insulation has been taken as 1.1 $W/m^2\ ^oC$. Thus the resulting calculated energy saving due to the edge insulation may either be taken as the result of reducing the floor U-value by 0.2 $W/m^2\ ^oC$ from 1.1 $W/m^2\ ^oC$, which is probably what would have actually happened, or as the result of reducing the U-value from 0.7 $W/m^2\ ^oC$ to 0.5 $W/m^2\ ^oC$, which is what theoretically ought to have happened.

Table 6.1 gives details of the various insulation measures, calculated annual space heating consumptions, energy savings and resulting house total heat losses. This shows that the insulation levels at Linford are likely to give space heating demands of almost a third of that of an equivalent reference house built to the 1976 standards or almost a half of that for one built to the 1982 standards. It also shows the large energy savings due to double glazing and wall insulation.

## 6.3 Air infiltration savings

### 6.3.1 Pressure test air leakage

As explained in Chapter 9, pressurisation tests on the Linford houses have shown that they are considerably more air tight than normal UK houses, including samples from the Neath Hill estate, though not up to Canadian or Swedish standards (see Figure 6.2).

There are energy savings associated with the low air leakage. These savings can roughly be broken down into those associated with design features, such as the choice of double glazing and the balanced flue boiler, and those specifically produced by draughtstripping.

Calculating the energy savings can only be done approximately, since there is no real direct relation between pressure test measurements and annual air infiltration heat losses. The relation is actually dependent on the nature and position of the cracks in the house, internal and external temperatures, wind speed, direction and the sheltering effect of adjacent buildings. Chapter 9 attempts to give an introduction to this extremely complex subject.

For the purpose of calculations here it has been assumed that houses have a continuous air infiltration rate which is proportional to the measured pressure test air leakage. A seasonal average air change rate of 0.32 ac/h, as calculated in section 9.6.1 for the test house is assumed to correspond to a measured test leakage of 8.9 ac/h. The average leakage of the occupied houses plus the test house was 7.9 ac/h (see Figure 6.2). The seasonal average infiltration rate has therefore been scaled in the proportion 7.9/8.9 giving an assumed state average infiltration of 0.28 ac/h. These infiltration rates relate to the houses with the windows shut. As variations in ventilation rate over the heating season is beyond the scope of the model, it has been crudely assumed that there is a further 0.1 ac/h, constant over the heating season, due to window opening.

### 6.3.2 Overall infiltration savings

Using this relation between pressure test leakage and seasonal average infiltration and ventilation rate, the Linford houses can be compared with the wider BRE sample of houses:

| | Air Leakage at 50 pa. | Seasonal Average infiltration rate | Seasonal Average infiltration + ventilation rate |
|---|---|---|---|
| | ac/h | ac/h | ac/h |
| BRE sample | 13.9 | 0.5 | 0.6 |
| Average Linford performance | 7.9 | 0.28 | 0.38 |
| Saving | | 0.22 | 0.22 |

For overall energy calculations, the reference house has been assumed to have an average air change rate of 0.6 ac/h and the Linford houses as built, one of 0.38 ac/h. The calculated energy savings as a result of this reduction, amounting to 1237 kWh/yr of useful space heating energy, are included in Table 6.1. More generally, the relation between pressure test leakage, assumed ventilation rate and house energy consumption is shown in Figure 6.3.

### 6.3.3 Draughtstripping savings

The doors of the Linford houses have all been draughtstripped after construction. Pressure tests on the test house before and after this was done show a significant reduction in air leakage:

| | Air Leakage at 50 pa | Seasonal Average infiltration |
|---|---|---|
| | ac/h | ac/h |
| Test House before draughtstripping | 9.9 | 0.36 |
| Test House after draughtstripping | 6.6 | 0.24 |
| Saving | | 0.12 |

This reduction in air change rate would be worth about 700 kWh/yr of useful space heating, but only if the draughtstripping performance were maintained over the whole year. In fact the houses were tested again 9 months later, by which time the air leakage had risen from 6.6 ac/h to 8.9 ac/h. There is no real way of telling whether this was due to a change in the building fabric or a deterioration in the performance of the draughtstripping, probably a combination of the two. It is thus likely that the draughtstripping is worth less than 700 kWh/yr and a round figure of 500 kWh/yr has been used for cost-effectiveness calculations.

It has been assumed that the BRE sample of 'normal' houses was not particularly well draughtstripped and thus that the 500 kWh/yr savings are included in the total 1237 kWh/yr overall building savings.

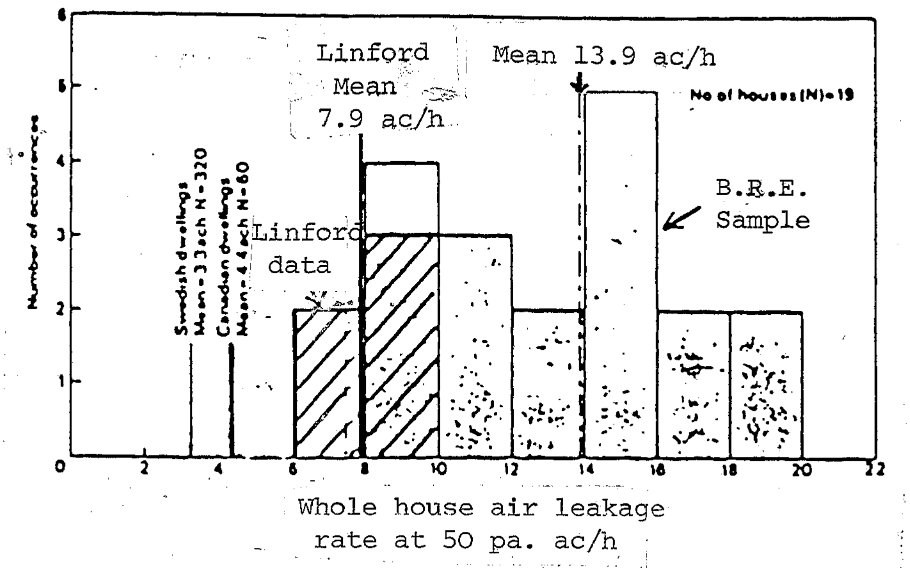



Figure 6.2 Air Leakage at 50 pa. for Linford Houses & a selection of UK, Canadian & Swedish houses

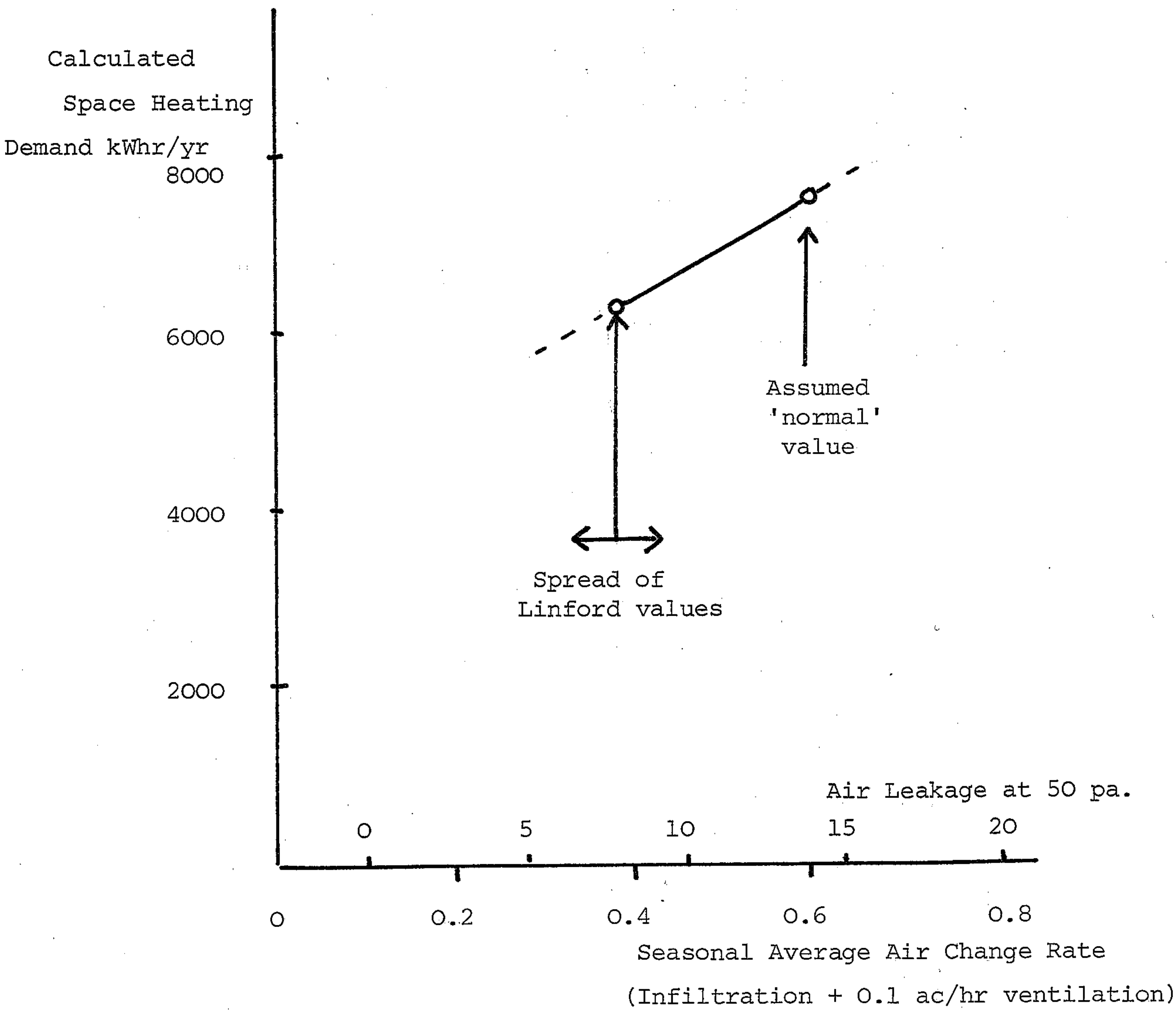



Figure 6.3 Assumed relation of air leakage, seasonal average air change rate and annual space heating demand

For costing purposes, the remaining energy savings have been shared equally between the double glazing, the balanced flue boiler and better design and construction techniques:

| Assumed cause | Saying |
|---|---|
| Draughtstripping (doors) | 500 kWh/yr |
| Double glazing (draughtstripping) | 246 kWh/yr |
| Balanced flue boiler | 246 kWh/yr |
| Better design and construction techniques | 245 kWh/yr |
| Total | 1237 kWh/yr |

6.3.4. Estate layout savings

As explained in Chapter 9, it would appear from the infiltration rate measurements on the test house that the presence of another house immediately to the south-west can have a significant sheltering effect from strong south-westerly winds. This sheltering has a consequent energy saving effect estimated at about 400 kWh/yr. Sheltering from north-easterly winds did not appear to be so important, but this may be due to the presence of a considerable number of houses and trees on that side of the Linford houses anyway.

These potential energy savings cannot really be claimed for the Linford houses, since it is likely that any 'normal' estate layout would have had an equivalent amount of mutual sheltering, but it should be borne in mind for future projects.

## 6.4 Marginal passive solar gains

These marginal passive solar gains are the energy savings due to correct orientation of the house, avoiding overshading, and concentrating glazing on the south side. They are not the same as the absolute solar gains that have been calculated in Chapter 12. Even a very ordinary house may have a large absolute solar input, but this is not the same as creating a saving in space heating energy. This matter is described in detail in Chapter 10.

These energy savings have been calculated using the NBSLD-based model, continuing from the insulation and air infiltration savings above. Starting from the reference house shell, insulated to the Linford level and with a low air change rate, the sequence of modifications in Figure 6.1 is continued. The house is initially assumed to be overshaded, face S.W./N.E. and be of dual aspect construction, with equal glazing on both facades. The sequence of modifications is as follows:

A) The replacement of the lightweight blockwork in the inner leaf of the external walls and the partition walls with dense concrete block. This is primarily to prevent summer overheating. It has a slight energy disbenefit since the external walls will have a slightly increased U-value and the extra thermal mass will encourage higher average internal house temperatures.

Table 6.2 Marginal Passive Solar Gains

| | Total Loss W/°C | Annual Space Heating kWhr/yr | Energy Saving kWhr/yr |
|---|---|---|---|
| Reference house shell from table 6.1 Dual aspect. SW facing overshaded, net curtains | 213 | 6344 | - |
| Replace lightweight block with dense concrete block | 215 | 6497 | -153 |
| Face south and avoid overshading | 215 | 6041 | 456 |
| Concentrate glazing on south side. 21.7 $m^2$ south facade 5.9 $m^2$ north facade | 215 | 5569 | 472 |
| Reduce window clutter | 215 | 5118 | 451 |

All energies are useful.

For cost-effectiveness purposes the average Linford performance has been taken as the average of the last two figures.

'Average' Linford space heating = 5343 kWhr/yr

Marginal passive solar gains excluding disbenefit of thermal mass
= 6497 - 5343 = 1154 kwh/yr

,, ,, ,, ,, including disbenefit of thermal mass
= 6344 - 5343 = 1001 kwh/yr

B) Remove the overshading and face the house south.

C) Concentrate the glazing on the south side.

D) Reduce the level of window clutter by removing net curtains.

The calculated space heating consumptions for the steps, together with energy savings are shown in Table 6.2.

These savings should be regarded as average estimates, since the figures are dependent on the length of the heating season, which is in turn a function of house internal temperatures and free heat gains, as explained in Chapter 10. The model has used, as far as possible average internal temperatures and free heat gains as recorded in the occupied houses. The weather data for the model, Kew 1969, is also conveniently similar to Milton Keynes 82/83 in terms of average temperatures and solar radiation.

The effective absorptivity of the windows, with and without net curtains has been derived from the thermal calibration experiments carried out on the test house.

From Table 6.2 it can be seen that increasing the thermal mass of the house causes a small increase in energy consumption of about 150 kWh/yr. The next three steps each produce a marginal passive solar energy saving of about 450 kWh/yr.

Since not all of the Linford houses had full net curtains, the average marginal passive solar saving has been taken as being halfway between the last two steps. It can either be taken as excluding the disbenefit due to the increased thermal mass and hence equal to 1154 kWh/yr, or including it, in which case the gains fall to 1001 kWhr/yr.

This energy saving figure does not assign any usefulness to the slight rise in average house internal temperature as a result of the solar improvements. This may tend to undervalue the benefits of the solar modifications at the end of the heating season, but, as explained in Chapter 12, it is difficult to draw the line between 'useful' and 'useless' solar gains.

## 6.5 Boiler efficiency savings

At the design stage it proved very difficult to get information on boiler efficiencies from manufacturers. It is thus likely that the reference house would have been fitted with a boiler of indifferent performance.

For the purpose of calculating savings it has been assumed that this boiler would have had similar properties to those installed on the Neath Hill estate, a conventionally flued, heavyweight boiler of similar size to that fitted at Linford.

As described in Chapter 12, boiler, or more accurately system efficiencies can be compared by plotting averages of gas input against average heat output. This type of plot gives an intercept on the X-axis of standing losses (mostly the pilot flame) and a slope of the asymptotic conversion efficiency, i.e. that efficiency that the boiler tends to approach at full output.

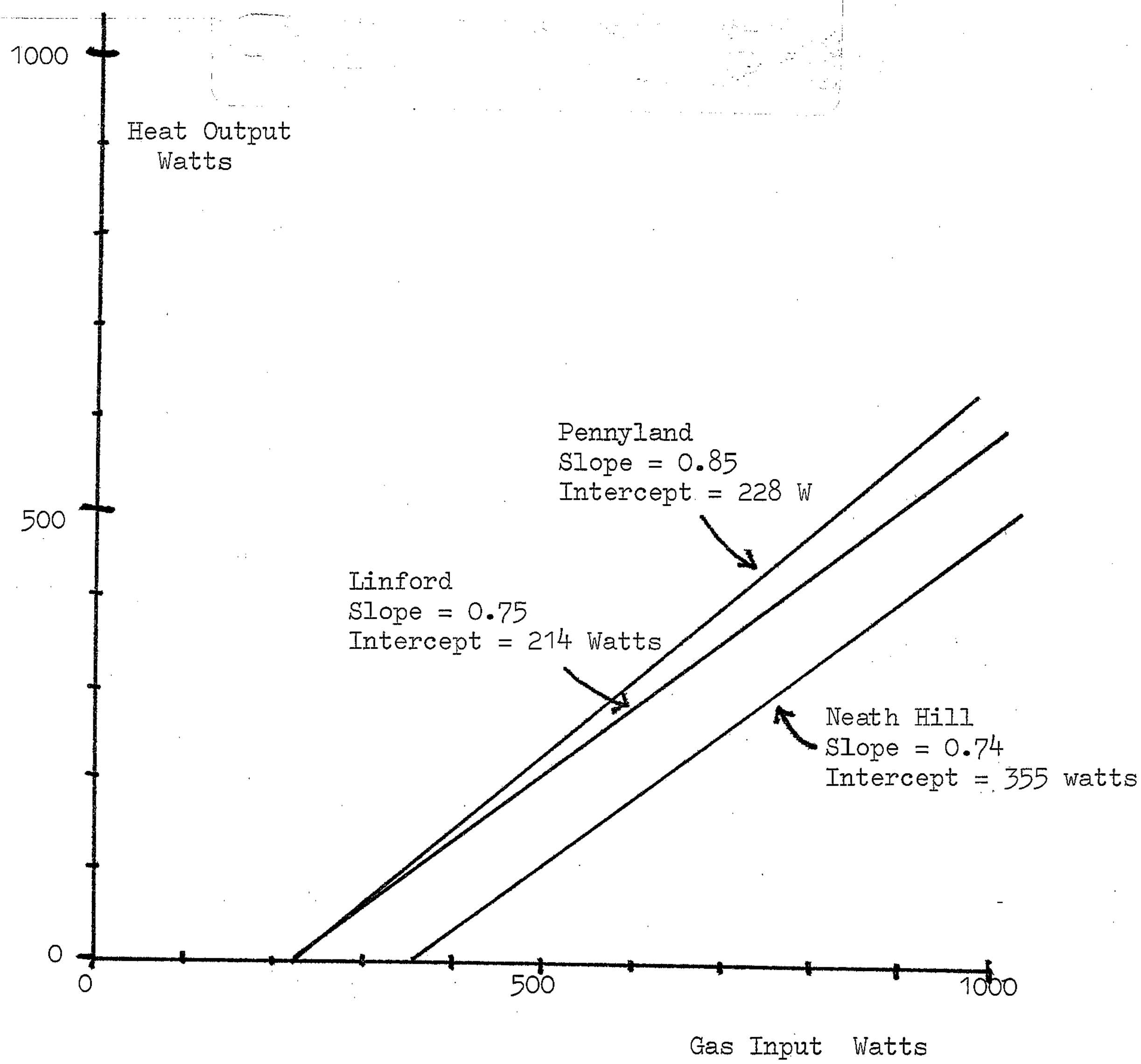



Figure 6.4 Average boiler efficiency plots for Linford, Pennyland and Neath Hill

Essentially the same monitoring equipment has been used to assess the Neath Hill, Pennyland and Linford boilers. Although the accuracy of the heat meters measuring the output of the boilers does leave a lot to be desired, it is possible to compare the average performance of the three systems.

Figure 6.5 shows the average efficiency plots of the three systems. This shows clearly that the Linford and Pennyland systems have lower standing losses than the Neath Hill boilers. The Linford and Neath Hill systems have about the same asymptotic efficiency. The Pennyland boilers, the smaller model of the Chaffoteaux boiler used at Linford, have a slightly higher asymptotic efficiency.

With typical heat meter errors of 5-10%, it is not possible to take the actual numerical values of the asymptotic efficiencies too seriously, though the estimates of standing losses are likely to be more accurate.

The main difference between the Linford and 'normal' Neath Hill systems would appear to be a reduction in standing losses from 355 watts to 214 watts. Some of this reduction is probably due to a smaller pilot flame, and some due to reduced boiler cycling losses because of the low thermal capacity. In the Bradville solar house project, for example, the pilot flame loss was reduced from 210 watts down to 100 watts merely by adjusting the pilot correctly (Reference 6.4).

These boiler standing losses are assumed to be 5% useful in winter and totally wasted in summer. In order to allow them to be included in the same energy saving graph as the other energy saving measures, they have been scaled from delivered energy to equivalent useful energy by the assumed common asymptotic boiler efficiency of 75%.

This gives equivalent useful energy standing losses of 2260 and 1360 kWh/yr for the two systems, a saving of 900 kWh/yr in equivalent useful terms or 1200 kWh/yr in delivered energy.

It should be stressed that although the two systems have the same asymptotic efficiency of about 75%, this does not include the standing losses. The actual average boiler efficiencies including these losses are much lower, typically 60-65%.

## 6.6 Total energy savings

It is now possible to put together a total picture of the project energy savings, though it must be stressed that no particular element can really be specified to better than ±30%. Figure 6.5 has been built up to show the total non-cooking gas consumption of the Linford house design under various assumptions about insulation, etc. This data is also set out numerically in Table 6.3. The total energy breakdown has been expressed in useful energy terms, and by including boiler standing losses can be translated into delivered energy, and hence money, by dividing by the asymptotic boiler efficiency of 75%.

Starting from the bottom of Figure 6.5 the diagram consists of:

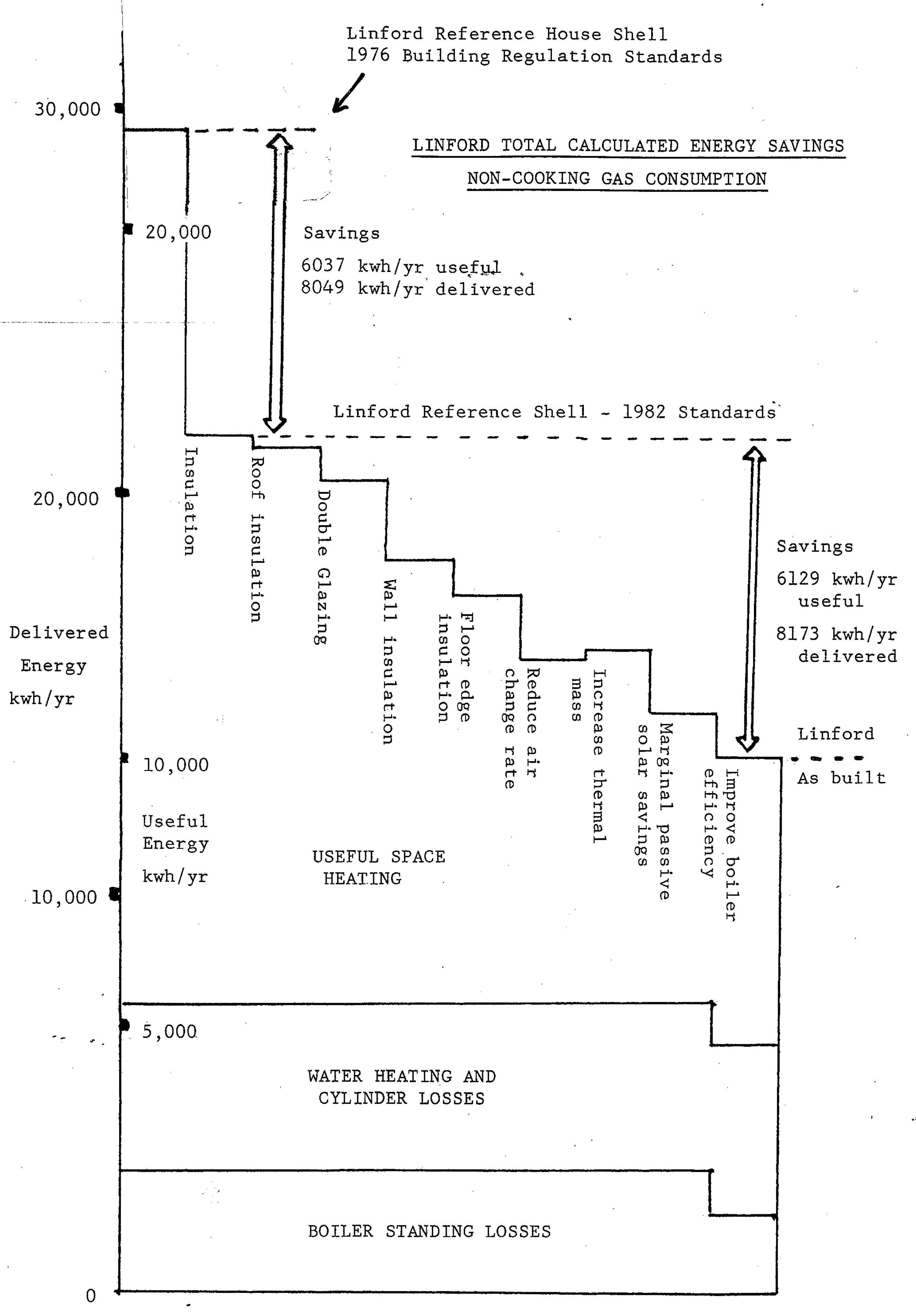

Linford Reference House Shell
1976 Building Regulation Standards
LINFORD TOTAL CALCULATED ENERGY SAVINGS
NON-COOKING GAS CONSUMPTION
30,000
20,000
Savings
6037 kwh/yr useful
8049 kwh/yr delivered
Linford Reference Shell - 1982 Standards
20,000
Insulation
Roof insulation
Double Glazing
Wall insulation
Floor edge insulation
Reduce air change rate
Increase thermal mass
Marginal passive solar savings
Improve boiler efficiency
Savings
6129 kwh/yr useful
8173 kwh/yr delivered
Delivered Energy kwh/yr
10,000
Useful Energy kwh/yr
Linford
As built
USEFUL SPACE HEATING
10,000
5,000
WATER HEATING AND CYLINDER LOSSES
BOILER STANDING LOSSES
0

Figure 6.5

LINFORD ENERGY SAVINGS

Table 6.3

All units are kwh/yr

| | 1976 Regs. | Add 50 mm roof insulation | Add 50 mm wall insulation | Double glaze 20.6 $m^2$ - 1982 Regs. reference house | Roof insulation | 7 $m^2$ double glazing | Wall insulation | Floor edge insulation | Reduce air change rate | Add thermal mass | Marginal passive solar gains | Boiler efficiency savings |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Useful space Heating | 16609 | 15901 | 11829 | 10572 | 10236 | 9689 | 8133 | 7581 | 6344 | 6497 | 5343 | 5343 |
| Useful water heating and tank losses | 3330 | 3330 | 3330 | 3330 | 3330 | 3330 | 3330 | 3330 | 3330 | 3330 | 3330 | 3330 |
| Equivalent useful boiler standing losses | 2260 | 2260 | 2260 | 2260 | 2260 | 2260 | 2260 | 2260 | 2260 | 2260 | 2260 | 1360 |
| Total equivalent useful energy | 22199 | 21491 | 17419 | 16162 | 15826 | 15279 | 13723 | 13171 | 11934 | 12087 | 10973 | 10033 |
| Delivered energy | 29599 | 28655 | 23225 | 21550 | 21101 | 20372 | 18297 | 17561 | 15912 | 16116 | 14577 | 13377 |
| Delivered energy saving | - | 944 | 5430 | 1675 | 449 | 729 | 2075 | 736 | 1649 | 204 | 1539 | 1200 |
| Reduction in house heat loss W/$^{o}$C | | 14 | 68 | 37 | 6 | 12 | 24 | 11 | 20 | -2 | 0 | 0 |

Linford as built

A) Boiler standing losses (pilot flame, cycling losses, etc.) expressed in equivalent useful energy terms.

B) Water heating energy including hot water cylinder losses. The typical Linford water heating energy consumption has been taken as 3330 kWh/yr (see Chapter 5). This amount includes heat losses to the house from the hot water cylinder of 3 kWh/day which are treated as useful free heat gains in winter and are included in the space heating model.

C) Useful space heating energy consumption as calculated by the NBSLD model.

Also included in Table 6.3 are the reductions in total house heat loss produced by various measures. These figures will be used in the next chapter to calculate cost savings produced as a result of having a smaller heating system.

The total package of measures has been estimated to reduce the delivered non-cooking gas consumption of the Linford houses to just over 45% of that of the equivalent 1976 Building Regulations standard house or 62% of that of the 1982 reference house design.

The delivered energy savings relative to the 1982 reference house can be broken down as follows:

| | Delivered energy saving kWh/yr | Percentage of total |
|---|---|---|
| Insulation | 3989 | 49 |
| Improved boiler efficiency | 1200 | 15 |
| Reduction in air change rate | 1649 | 20 |
| Marginal passive solar gains (including thermal mass effects) | 1335 | 16 |
| Total | 8173 | 100 |

These savings are compared with their relative costs in the next chapter.

## 6.7 Comparisons with Pennyland measurements

Although the Linford project has demonstrated that the houses have a low energy consumption, with space heating demands in the range 3500-8000 kWh/yr, the energy savings are merely the product of extensive computer modelling. As such, they may lack a certain amount of credibility. This situation can be considerably improved by comparing the results of a similar calculation process for the Pennyland project with actual measured gas consumptions for four of the project house groups.

Figure 6.6 shows the analogous Pennyland graph to Figure 6.5. It differs slightly in that since the project contains an improvement in marginal boiler efficiency, the Neath Hill delivered energy scale, to the left, differs from the Pennyland scale, to the right.

It should also be borne in mind that the Pennyland houses are smaller than the Linford houses, typically end of terrace houses with about 90 $m^2$ of floor area and about a half of the glazing area used at Linford. The energy savings for any particular measure are thus smaller.

Although the energy savings of various measures have been calculated in a slightly different order to that of Figure 6.5, three of the insulation levels approximately correspond. The 1976 Building Regulation level used in the Linford calculations corresponds to the Neath Hill uninsulated group. The 1982 Regulations level roughly corresponds to the Neath Hill insulated group (there is a small discrepancy in roof insulation level), and the Pennyland area 2 houses correspond to the Linford houses as built. The Pennyland area 1 houses roughly correspond to the 1982 Regulations level for Linford, except that they incorporate the high efficiency boiler and have a low air change rate.

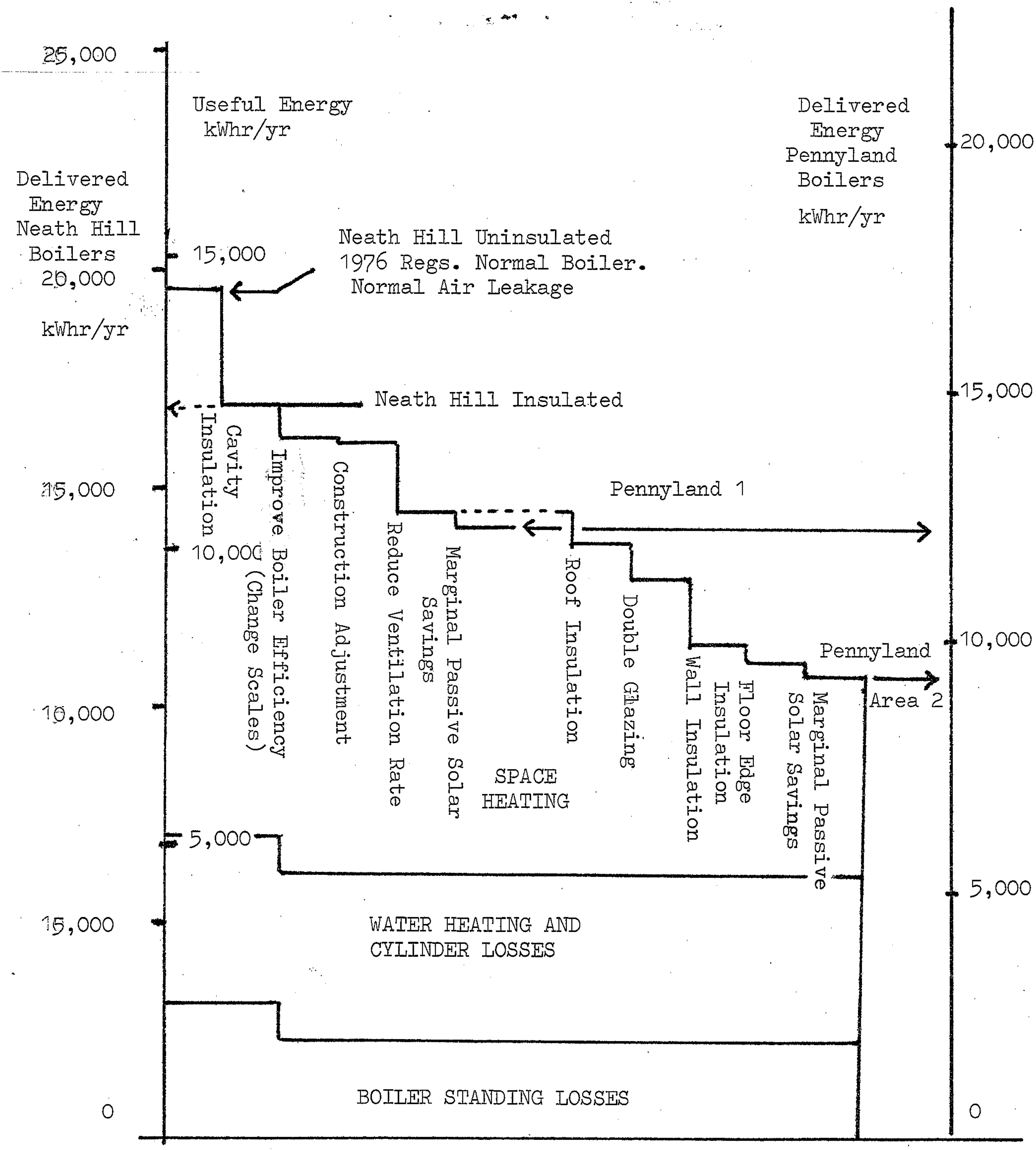
The four non-cooking gas consumptions for these groups are given below as derived from Figure 6.6. These can be compared with measured group gas consumptions for the 81/82 heating season if two minor corrections are made. It is necessary to add about 1000 kWh/yr to each group to allow for typical estate average gas cooking consumption and a further 1000 kWh/yr to compensate for the slight difference in average winter temperature between the model weather data, Kew 1969, and Milton Keynes weather for the 81/82 season, a matter of about 1°C.

| | Delivered non-cooking gas consumption kWh/yr | Corrected for cooking and temperature kWh/yr |
|---|---|---|
| Neath Hill uninsulated | 20941 | 22941 |
| Neath Hill insulated | 16984 | 18984 |
| Pennyland area 1 | 12361 | 14361 |
| Pennyland area 2 | 9288 | 11288 |

The resulting total gas consumptions are plotted, together with histograms of measured gas consumptions in Figure 6.7.

Although this process is very crude and takes no account of group variations in internal temperatues and free heat gains, the agreement is quite comforting. For comparison, the calculated figures for Linford for the three comparable insulation levels have also been plotted. These show the considerable energy penalty paid for a 20% increase in floor area, coupled with the dubious benefits of living in a detached, rather than a terrace, house.

Figure 6.7 also shows the difficulties that arise in determining energy savings by simple comparison of different house groups. Occupant variations in choice of temperatures and free heat gains can completely swamp differences in energy consumption due to changes in house insulation level. This subject is dealt with in detail in the companion Pennyland report.



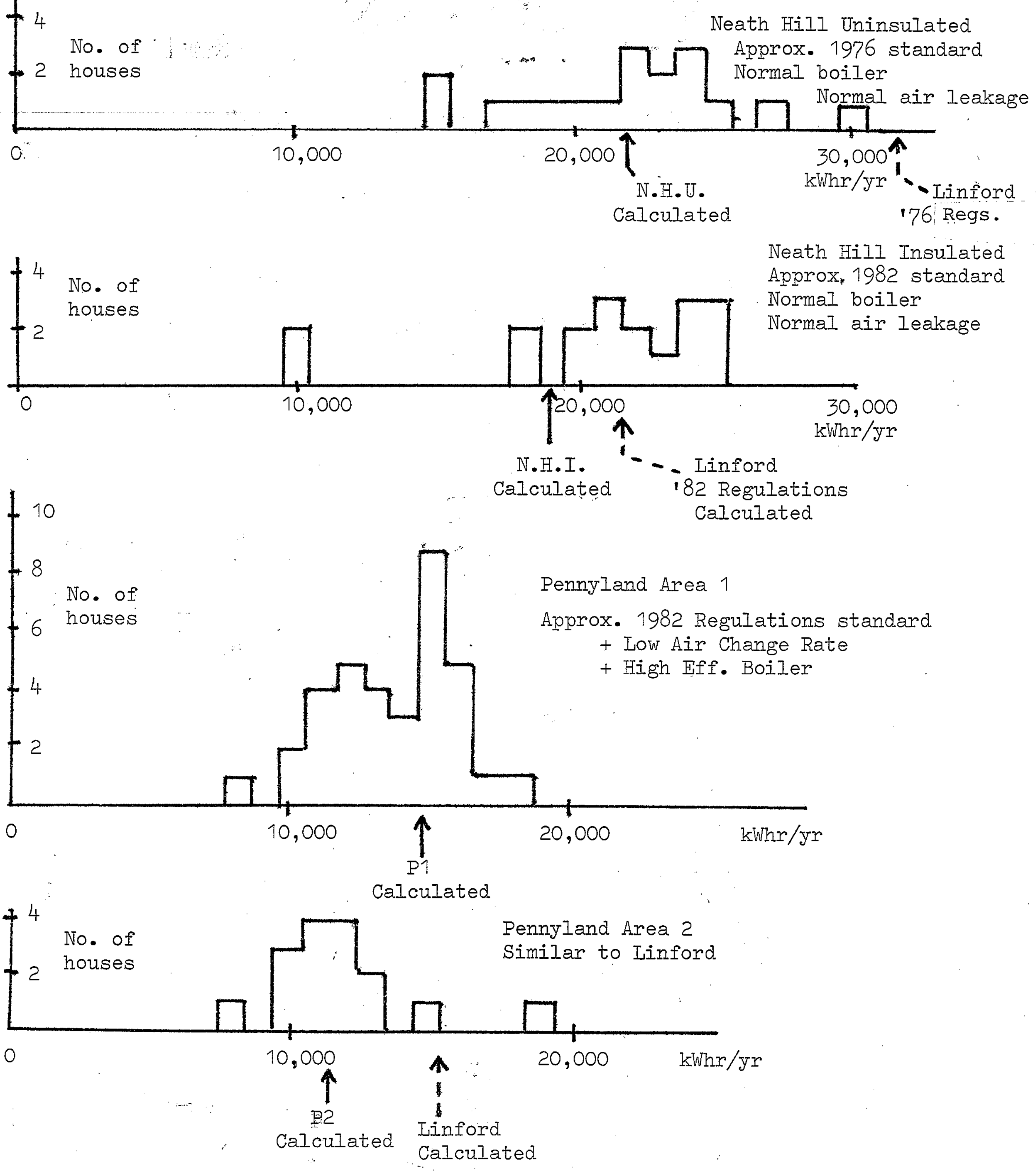

All calculations are for a 3 bedroom end of terrace house.

Figure 6.6 Pennyland and Neath Hill total energy savings non-cooking gas consumption

Figure 6.7 PENNYLAND AND NEATH HILL MEASURED AND MODELLED ENERGY CONSUMPTIONS

October 1981 - September 1982
Delivered Energy

Total Non-cooking Gas Consumptions




All houses are 3 bedroom type of nominally similar size.

## 6.8 Future possibilities

The experimental measurements have indicated five areas where further energy savings or construction cost savings could be made. A smaller boiler could save both energy and capital cost. Reduced window area and thermal mass could save on construction costs with little difference to house energy consumption. Improved hot water cylinder insulation could save energy for a small extra cost and full underfloor insulation might save a considerable amount of energy but probably involving considerable extra costs.

The energy savings of these five modifications are shown in Table 6.4, continuing on from the steps in Table 6.3. They are also plotted out in Figure 6.8, continuing on from Figure 6.5.

### 6.8.1 Smaller boiler

As indicated in Chapter 12, the installed boiler is rather too large for the house heat load and a smaller one of about 11 kW rating would be more appropriate. It is likely that being a better match to the building requirements it would have a higher marginal efficiency than the 75% measured for the installed system. It is not likely that the high value of 85% suggested for the Pennyland boilers would be reached (see Figure 6.4) and a figure of 80% has been assumed. The effect of this is a delivered energy saving of just over 700 kWh/yr.

Note that in Table 6.4 and Figure 6.8 this change in efficiency involves a slight increase in equivalent useful boiler standing losses, though these losses will still represent the same delivered energy.

### 6.8.2. Reduction of window area

It would appear that significant cost reductions can be made by reducing the south-facing window area slightly, from 21.7 $m^2$ to 18.7 $m^2$. This has almost no effect on house energy consumption. A small energy saving is possible by reducing the north-facing window area by 1 $m^2$. The overall energy saving of these two adjustments amounts to just under 100 kWh/yr of delivered energy, assessed on the basis of a house with half net curtains, in line with the 'average' Linford solar performance. The reduced window area also cuts the total house heat loss by 9 W/$^{\circ}$C, with consequent heating system sizing savings.

### 6.8.3 Reduction in thermal mass

In view of the poor penetration of solar gains into the north side of the building, some cost savings can be made by replacing the dense concrete blockwork on that side with normal lightweight block. This is likely to have little effect on house energy consumption or on peak summer temperatures in the south-facing rooms.

### 6.8.4 Better hot water cylinder insulation

The high heat losses from the hot water storage tank of about 3 kWh/day (see Chapter 11) could be halved for a relatively small extra cost in tank and pipe insulation. This would save about 550 kWh/yr of useful water heating energy. It would, though cause a slight increase in annual space heating load because of the smaller free heat gains. This reduces the overall saving by about a half.

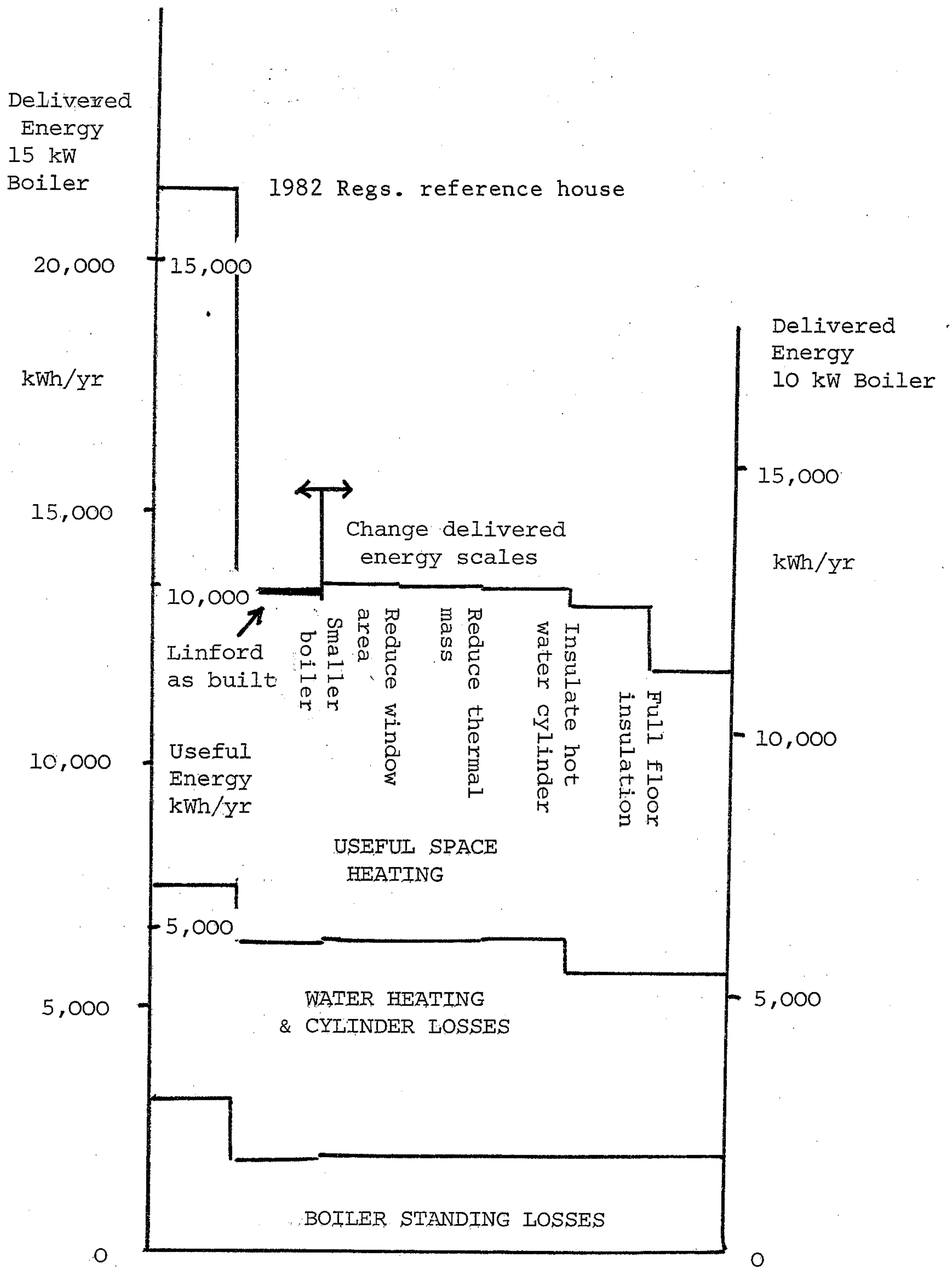
### 6.8.5 Full underfloor insulation

The large floor heat losses could be drastically cut by full underfloor insulation. It has been assumed that 50 mm of insulation extending under the whole floor, including the internal partition walls, would reduce the floor U-value from 0.9 $W/m^2\,{}^{o}C$ to 0.5 $W/m^2\,{}^{o}C$. This would have a significant effect on the house performance, reducing the space heating demand by about 1000 kWh/yr and also cutting the total house heat loss by 22 $W/{}^{o}C$, allowing further reductions in the installed heating system size.

Table 6.4 Possible future energy and cost savings

| All units are kWh/yr | Linford as built | Smaller boiler | Reduced window area | Reduced thermal mass | Hot water cylinder insulation | Full underfloor insulation |
|---|---|---|---|---|---|---|
| Useful space heating | 5343 | 5343 | 5266 | 5066 | 5350 | 4331 |
| Useful water heating and tank losses | 3330 | 3330 | 3330 | 3330 | 2784 | 2784 |
| Equivalent useful boiler standing losses | 1360 | 1450 | 1450 | 1450 | 1450 | 1450 |
| Total equivalent useful energy | 10033 | 10123 | 10046 | 9846 | 9584 | 8565 |
| Delivered energy | 13377 | 12654 | 12558 | 12308 | 11980 | 10706 |
| Delivered energy saving | - | 723 | 96 | 250 | 328 | 1274 |
| Reduction in house heat loss $W/{}^{o}C$ | - | - | 9 | 0 | 0 | 22 |

Figure 6.8 FUTURE POSSIBILITIES



## 6.8.6 The Linford house of the future

The final picture is thus of a house with an annual delivered energy use for water and space heating of just over 10,000 kWh/yr, about a third of that of the reference house shell built to 1976 standards and about a half of that for the 1982 standards. Nor have the energy conservation possibilities ended. The total heat requirement is now so low that it is approximately equivalent to ten gas boiler pilot flames burning throughout the year. The development of spark ignition boilers could eliminate one of these ten flames, though some care would have to be taken not to substitute an electrical standing loss for a gas one.

The boiler efficiency could still be improved on by the use of the new range of condensing boilers now available on the continent. These are likely to have marginal efficiencies approaching 95%.

As will be explained in the next chapter, it is likely for cost reasons that the large south-facing glazing would be reduced in area slightly. This would still leave a large proportion of the house heat loss as due to the windows. It might be possible to reduce the losses here with the use of low-emissivity films, but the reduced transmission could seriously reduce the passive solar gains.

A solar water heater still remains an option for the future. A 5 $m^2$ solar panel could supply 30% of the useful water heating demand, though the likely payback time of 30 years is rather unattractive.

The most promising area for future savings is in small scale combined heat and power generation. In the Linford houses the occupants' electricity bills are about equal to their gas bills and some attention should be paid to cutting electricity costs. Electricity generation is normally only 30% thermally efficient, mainly due to the enormous wastage of heat in cooling towers. Small scale cogeneration would allow the waste heat from electricity generation to be used to heat the houses. This could potentially produce further energy savings of the order of £100/yr with payback times of less than five years, though it would have to be organised on an estate-wide basis.

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6.2 P. Warren — Air infiltration in UK houses, Proc. CIB W67, 3rd International Symposium, An Foras Forbatha, Dublin, 1982.

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# 7. COST EFFECTIVENESS & MARKETABILITY

CONTENTS



In this chapter, the energy savings calculated in chapter 6 are translated into savings on fuel costs. These are compared with the capital costs of of the energy-saving measures to judge their cost-effectiveness.

Also the attitudes of the developers, estate agents and housebuyers towards the low energy house design are discussed.

The topics discussed in this chapter are quite complex and some readers may prefer simply to read the conclusions.

# 7. COST EFFECTIVENESS AND MARKETABILITY

## 7.1. Introduction

The previous chapter dealt with the analysis of the overall building performance in energy terms alone. In this chapter we introduce the extra dimension of the construction cost of each energy saving measure to be balanced against the fuel saving. By combining these we arrive at the overall cost-effectiveness of each measure as well as the total project savings.

Detailed costings have been carried out by Davis, Belfield and Everest Ltd., a firm of chartered quantity surveyors and authors of Spon's Guide, a standard reference work on building costs.

In addition to costs, there is also the consideration of the marketability of the houses. Designing low energy houses is not simply a question of minimising costs or even of maximising energy efficiency. At the end of the day, each house is someone's home. It must be pleasant to live in and, from the developer's point of view, must be a saleable item. Indeed the subject of the 'optimum' cost-effective window area can only be resolved by referring to the marketability of the house.

## 7.2. Choice of Reference House

As explained in chapter 2, the Linford houses were essentially designed in 1978. Most of the energy saving features were chosen and their cost-effectiveness assessed at that time. As such the baseline reference for analysis was the 1976 Building Regulation Standards and then current building practice. The Linford houses thus represent an educated guess at that time of what a good cost-effective low energy house should be like. The guess was considerably clouded by lack of basic information on house energy performance, detailed costs and matters such as the sizing of a suitable heating system.

Since then, the world has moved on. The performance of the houses has been assessed in detail and the cost-effectiveness has to be calculated in present day terms. This has meant inserting a new baseline for assessment, that of the 1982 Building Regulation insulation standards.

As explained in the previous chapter, since there are no 'normal' houses for comparison for the Linford project, the performance has been compared with two fictitious 'reference' house designs. One represents the house that probably would have been built instead of the Linford design in 1980. As such it would have been built to the 1976 insulation levels of insulation and it has been taken to have the same levels of air leakage and boiler efficiency as found from the measurements on the Neath Hill estate (built 1978) which has acted as control group for the Pennyland project. The second reference house represents current 'middle of the road' building practice. It has insulation to the improved 1982 standards, while keeping the same air leakage and boiler efficiency.

From a solar point of view, the reference houses have been chosen to have the same total window area as the Linford houses, in order to demonstrate the energy benefits of the simple passive solar measures of avoiding overshading, correct orientation and redistribution of glazing.

This does pose a slight problem with regard to satisfying the 1982 regulations. These limit the area of permitted single glazing to 12% of the perimeter wall surface area, unless extra insulation is incorporated to compensate. This would limit the reference house to only 17 $m^2$ of glazing. In order to bring the total area up to 27.6 $m^2$, it has been necessary to assume that 20.6 $m^2$ of it is double glazed.

It must be said that the large windows do have a significant cost penalty, and that the Linford houses in no way represent a cost-optimum design. Given the past uncertainties, it would be surprising if they were. It is thus possible to specify a cheaper design of reference house for the same energy performance, just as it is also possible to do so for the Linford design. This is discussed under future possibilities at the end of this chapter.

## 7.3. Costs

No detailed costs were made at the time of construction. Indeed, given the wide practical variation in labour costs from one house to another, it was felt at the time to be an almost impossible task. The costs in this chapter have been prepared in a standard manner as used for ETSU's evaluation of other passive solar house designs.

Table 7.1 gives a breakdown of the total cost of the Linford house design as estimated for construction in March 1984. Note that the areas quoted for costing may differ slightly from the areas used for thermal calculations.

Table 7.1 Total Costs

| | $m^2$ | £ | £/$m^2$ |
|---|---|---|---|
| 1. Substructure and ground floor | 57 | 2698 | 47.3 |
| 2. Upper floors | 54 | 1629 | 30.2 |
| 3. Staircase | - | 679 | - |
| 4. Roof | 80 | 3575 | 44.7 |
| 5. External Walls | 136 | 5422 | 39.8 |
| 6. Windows and External Doors | 37 | 3742 | 101.1 |
| 7. Internal Walls | 91 | 1823 | 20.0 |
| 8. Internal Doors | - | 1436 | - |
| 9. Mechanical Services | - | 4761 | - |
| 10. Electrical Services | - | 1115 | - |
| 11. Sundries | - | 1583 | - |
| | | 28463 | |

One point to note in this table is that windows cost about £60/m$^2$ more than walls. A small part of this is due to the fact that the costings include such items as lintels and cavity closers around the windows in the window costs, but there is a major cost difference.

Table 7.2 below sets out the marginal costs of the energy saving measures, progressing from the 1976 reference house through the 1982 design to the Linford design as built.

Table 7.2 Marginal Extra Costs

| Item | Area m$^2$ | Cost £ | Unit cost £/m$^2$ |
|---|---|---|---|
| 1976 Reference House | | | |
| 1. Roof insulation 50 mm to 100 mm | 80 | 35 | 0.43 |
| 2. Wall insulation 0 to 50 mm | 136 | 389 | 2.86 |
| 3. 20.6 m$^2$ Double Glazing | 20.6 | 0 | 0 |
| | | 424 | |
| 1982 Reference House | | | |
| 4. Roof insulation 100 mm to 150 mm | 80 | 75 | 0.94 |
| 5. 7 m$^2$ Double Glazing | 7 | 0 | 0 |
| 6. Wall insulation 50 mm to 100 mm | 136 | 170 | 1.25 |
| 7. Floor slab edge insulation | 57 | 53 | 0.93 |
| 8. Draught Stripping | - | 31 | - |
| 9. Thermal Mass - Dense Blockwork | 196 | 155 | 0.79 |
| 10. Low thermal capacity boiler | - | 0 | - |
| | | 484 | |
| Linford as Built | | | |
| Total Linford as built over 1976 reference design | | 908 | |

There are many comments that can be made about the contents of this table:-

Roof Insulation

The first increase in roof insulation, from 50 mm to 100 mm is far cheeper than the increase from 100 to 150 mm, although the actual extra quantity of insulation is the same. This appears to be due to the extra handling costs of the considerable bulk of material.

Wall Insulation

The cost of the first 50 mm of cavity insulation is far higher than that of the next 50 mm. This is because of the basic fixing and handling costs associated with having any cavity insulation at all. Once these costs have been taken into account, then the extra marginal cost of wall insulation is quite low. The costs of increasing the insulation from 50 mm to 100 mm include the extra costs of more brickwork in the external walls and an increased roof area in order to maintain the same house internal floor area.

Double Glazing

It may seem quite extraordinary that the Sashless double glazing should cost no more than conventional single glazing. The reason is basically the substitution of thicker glass for complex and expensive framing in conventional windows. The Sashless window thus has less woodwork and ironmongery than a normal window. The price differential is to a certain extent dependent on the size and complexity of the window, but price comparisons for three typical sizes of window, as shown in figure 7.1, only show a significant price difference for the very smallest area units. Conventional double glazing is about £22/$m^2$ more expensive.

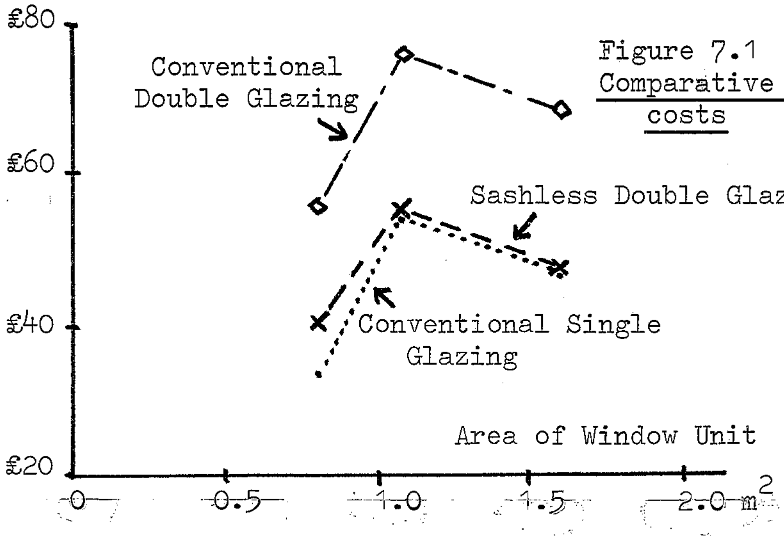



Figure 7.1
Comparative glazing costs

As noted in chapter 4, the Sashless windows do have certain defects in use, but this has to be weighed against the cost saving of £600/house compared to conventional double glazing.

Draught Stripping

The cost of £31 here represents that of sealing round three external doors and was mainly carried out because of the visible warping of the french windows in the living room. As mentioned in chapter 4, this draught stripping could have been made easier( and cheaper) by better door detailing.

Boiler

The Linford houses were fitted with a low thermal capacity boiler with a balanced flue. The reference houses have been assumed to have a conventionally flued heavyweight boiler, as fitted at Neath Hill.

The cost difference between these options appears to be zero, indeed the balanced flue arrangement may be up to £100 cheaper than the conventional flue.

Thermal Mass

This has turned out to be a surprisingly large cost extra. Although the cost per square metre is low, the energy brief included dense concrete blockwork in the inner leaf of the whole area of the external walls as well as most of the area of internal partition walls. This adds up to almost 200 $m^2$ and an extra cost of £155.

The insistence on a high level of thermal mass reflects a genuine concern about the possibility of summer overheating and a desire not to repeat the experience of the Bradville active solar house. This managed to produce a newspaper headline 'COUPLE ROAST IN SOLAR HOUSE', though it was later conceded that the house was no hotter than the non-solar house next door. The degree to which the thermal mass might be reduced is discussed later.

Finally it is worth noting that the total extra energy saving costs only amount to about 3% of the total construction cost of the house.

## 7.4. Heating System Savings

The extra costs of insulation can, to a small extent be offset by the reduced costs of the heating system. It was difficult to explore this at the design stage, given the uncertainties over methods for sizing systems for low energy houses. The measurements described in chapter 14, especially the performance through some of the coldest weather this century, have given considerable confidence in this area.

The system savings split into two parts, savings due to reduced radiator sizes and those due to reduced boiler sizes. Since radiators come in a wide range of sizes and there are a large number in a house, radiator costs tend to be a fairly smooth function of the calculated fabric heat loss of the house. Boilers, on the other hand, come in a restricted range of sizes, with a step in output power of about 4 kW between them. Thus in comparing two house designs, boiler cost savings (around £60 per 4kW step) may suddenly appear at rather abitrary points. In order to get round this problem the total radiator and boiler costs have been worked out for the 1976 and 1982 reference houses as well as the Linford houses as built and have been plotted against the total house fabric heat loss as calculated by the NBSLD model (see fig. 7.2). From this we can calculate an average heating system cost saving per unit reduction in house heat loss.

When the Linford houses were designed there was only a limited range of low thermal capacity boilers available. The Chaffoteaux Miniflame, rated at 8.2 kW, appeared too small and the Maxiflame, as fitted, was rather too large, being rated at 17.6 kW. Since this lack of availability tends to penalise the Linford house design unnecessarily, costings have been carried out on the basis that the Linford and 1982 reference house have been fitted with a Corvec 45 boiler, rated at 13.2 kW. The 1976 reference house requires the 17.6 kW Maxiflame.

The precise method used for sizing the Linford radiators is not known, since the contractor responsible could not be contacted. The installed radiators do appear to correspond to a standard sizing method using the following assumed temperatures:-

| | |
|---|---|
| External Temperature | -1°C |
| Living room, kitchen, dining room, bathroom | 21°C |
| Hall, bedrooms and W.C.s | 18°C |

Taking these internal temperatures and an average house air change rate of 1 ac/h, then there appears to be an extra allowance of +40% on all radiators. How much of this allowance is for warm-up and how much caution in the face of an unusual house design is not known, but this kind of figure is not difficult to justify given a heavyweight structure.

This method has been used for the 1976 and 1982 reference house designs, to allow costing on a common basis. Fabric U-values for system sizing have been taken on a 'book value' or 'worst-case' basis, rather than the 'best guess of actual performance' basis used for the energy modelling. Hence there may be some discrepancies in the heat loss figures quoted.

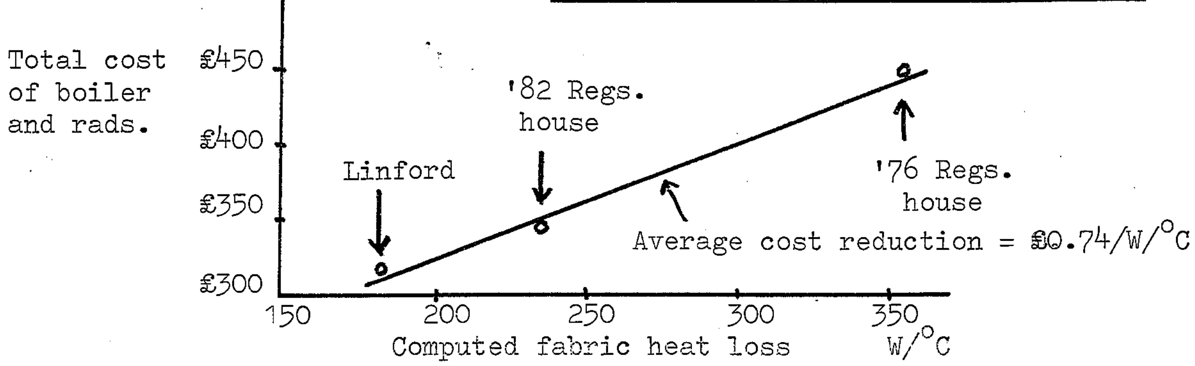
It is perhaps worth noting that there may be an extra 'thermal mass' cost here, in the shape of an increased heating system size to cope with notions of a longer warm-up time. This may amount to a 20% oversizing or an extra cost of about £30.

Table 7.3 below gives the calculated radiator and boiler sizes and their costs. The costs have been taken on an ex-warehouse basis, with full trade discounts and thus do not include the heating contractor's handling costs or his profit margin. This may thus underestimatedthe overall savings slightly.

Table 7.3 Heating System Sizes and Costs

| House | Radiator Capacity kW | Water Htg. Load kW | Total Load kW | Assumed Boiler kW | Rads. £ | Costs Boiler £ | Total £ |
|---|---|---|---|---|---|---|---|
| Linford | 7.1 | 3 | 10.1 | 13.2 | 131 | 188 | 319 |
| '82 Regs. | 8.9 | 3 | 11.9 | 13.2 | 156 | 188 | 344 |
| '76 Regs. | 12.4 | 3 | 15.4 | 17.6 | 212 | 234 | 446 |

Figure 7.2. Average Heating System Cost Reduction



The average heating system cost saving derived from figure 7.2 is thus £0.74 for every W/°C reduction in house heat loss. Only insulation measures have been included in this calculation, since heating system designers are unlikely to know the actual house air change rates or to take any account of solar gains.

## 7.5. Energy Savings

The energy savings have been calculated in the previous chapter. These show a total delivered energy saving of 16222 kWh/yr, broken down as in Table 6.3. These savings have been costed using a delivered gas price of 33.5p/therm, equivalent to a marginal delivered fuel cost of 1.14 p/kWh. Given the marginal boiler efficiency of 75%, this gives a useful fuel price of 1.5 p/kwh.

The contribution of the individual energy saving measures is shown below:-

Table 7.4 Energy Savings

| Measure | Delivered fuel saving kWh/yr | Value £/yr |
|---|---|---|
| 1976 Regulations reference | | |
| 1. Increased roof insulation | 944 | 10.8 |
| 2. Increased wall insulation | 5430 | 61.9 |
| 3. 20.6 $m^2$ double glazing | 1675 | 19.1 |
| | 8049 | 91.8 |
| 1982 Regulations reference | | |
| 4. Increased roof insulation | 449 | 5.1 |
| 5. 7 $m^2$ double glazing | 729 | 8.3 |
| 6. Increased wall insulation | 2075 | 23.7 |
| 7. Floor edge insulation | 736 | 8.4 |
| 8. Air infiltration reduction | 1649 | 18.8 |
| 9. Additional thermal mass | -204 | -2.3 |
| 10. Marginal passive solar gains | 1539 | 17.5 |
| 11. Boiler efficiency savings | 1200 | 13.7 |
| | 8173 | 93.2 |
| Linford as Built | | |
| Total Linford as Built to '76 Regs. | 16222 | 185.0 |

## 7.6. Cost Effectiveness

By bringing together the extra construction costs, the heating system savings and the annual fuel savings, it is now possible to assess the payback times of the various measures. These are set out in Table 7.5 below. The heating system savings have been apportioned using the reductions in house heat loss calculated in Table 6.3 for insulation measures alone, together with the figure of £0.74 per W/°C from figure 7.2.

Table 7.5 Cost-Effectiveness of Measures

| Measure | Cost Extra £ | Heating System Saving £ | Net Cost Extra £ | Fuel Saving £/yr | Payback Time yrs |
|---|---|---|---|---|---|
| '76 Regs. Reference | | | | | |
| 1. Roof ins. 50-100 mm | 35 | 10 | 25 | 10.8 | 2.3 |
| 2. Wall ins. 0 - 50 mm | 389 | 50 | 339 | 61.9 | 5.5 |
| 3. Double glaze | 0 | 27 | -27 | 19.1 | 0 |
| | 424 | 87 | 337 | 91.8 | 3.7 |
| '82 Regs. Reference | | | | | |
| 4. Roof ins. 100-150 mm | 75 | 4 | 71 | 5.1 | 13.9 |
| 5. Double glaze | 0 | 9 | -9 | 8.3 | 0 |
| 6. Wall ins. 50-100 mm | 170 | 18 | 152 | 23.7 | 6.4 |
| 7. Floor edge ins. | 53 | 8 | 45 | 8.4 | 5.4 |
| 8. Reduced infiltration rate. | 31 | 0 | 31 | 18.8 | 1.6 |
| 9. Passive solar gains + thermal mass | 155 | 0 | 155 | 15.2 | 10.2 |
| 10. Improved boiler eff. | 0 | 0 | 0 | 13.7 | 0 |
| | 484 | 39 | 445 | 93.2 | 4.8 |
| Linford as Built | | | | | |
| Total Linford as Built to '76 Regs. Reference | 908 | 126 | 782 | 185 | 4.2 |

The overall performance appears to be excellent, with payback times of under five years for both design steps. This is far better than the original expectations of an overall payback of 10 - 15 years, as noted in chapter 2. The Linford house design, compared to the 1976 Regulations reference house ( what would have been built in its place in 1980 ) saves an estimated £185 of fuel a year with a payback time of 4.2 years. Compared to the 1982 Regulations reference ( what would probably have been built in its place in 1983 ), the saving is an estimated £93/yr. with a payback time of 4.8 years.

The overall payback times are perhaps sufficiently short not to require much comment except to say that considerations of future real fuel price rises and the tax-deductible nature of mortgage interest would reduce the real financial payback time for a house buyer even further.

As noted in chapter 6, the credibility of the overall fuel saving figure of £185/yr. perhaps rests with the results of the Pennyland demonstration project, where actual fuel consumptions of houses at different insulation levels have actually been measured, as well as being modelled. The Pennyland project addresses the real statistical difficulties of determining real fuel saving differences between house designs. In practice, the fuel savings and payback times quoted in Table 7.5 are likely to have error limits of at least ± 30%, and do need a certain amount of qualification in some cases.

## 7.7 Ranking the Measures

In spite of the uncertainties in the figures, it is worth ranking all the measures to see what are the most worthwhile methods of reducing fuel bills. They can be set out in order:-

Table 7.6 Rank Order of Measures

| Item | Payback Time Years |
|---|---|
| 1976 Reference House | |
| 1. Double Glazing | 0 |
| 2. Roof Insulation 50 mm - 100 mm | 2.3 |
| 3. Wall Insulation 0 - 50 mm | 5.5 |
| 1982 Reference House | |
| 4. Double Glazing | 0 |
| 5. More Efficient Boiler | 0 |
| 6. Infiltration Reduction | 1.6 |
| 7. Floor Edge Insulation | 5.4 |
| 8. Wall Insulation | 6.4 |
| 9. Passive Solar Gains | 10.2 |
| 10. Roof Insulation 100 mm - 150 mm | 13.9 |
| Linford as Built | |

The most cost effective measure is that of the Sashless double glazing. Not only does this have an almost zero extra cost, but it actually saves on heating system costs as well. Thus 15% of the overall £185 fuel saving can be achieved with a net reduction in total house construction cost of £36.

The next most cost-effective measure is that of using a high efficiency boiler with a balanced flue. As previously noted, the low thermal capacity boiler itself is unlikely to cost any more than a conventional heavyweight boiler. The balanced flue assembly may actually be £100 cheaper than a conventional flue. Thus a contribution of £13.7/yr in fuel saving can be acheived for no extra cost.

Reducing air infiltration saves an estimated £18.8/yr. It is, though, very difficult to assign a real cost to this item. The draught-stripping of the external doors is the only really visible cost, amounting to £31. This really only applies to a small proportion of the total infiltration saving, an amount estimated to be about 500 kWh/yr useful, or £7.5/yr (see chapter 6). Taken on its own, this would have a payback time of 4 years.

In practice the actual costing of the reduced infiltration rate may be almost impossible. It is in part due to the performance of the double glazed windows, the provision of draught lobbies ( which are likely to have costs of about £200 each ), the draught-stripping and care in sealing around pipes. Then there is also the air leakage of the conventional boiler flue and such considerations as the impermeability of the dense concrete blockwork and the quality of plastering. It is thus clear that the figure of 1.6 years for the payback time should be regarded with caution.

Increasing the roof insulation from 50mm to 100 mm is very cost-effective, with a payback time of 2.3 years. The next step increase, from 100 mm to 150 mm is very much less cost-effective, having a payback time of over ten years. This is in part due to a law of decreasing energy returns as the insulation is increased in thickness and partly due to the considerably higher cost of the second step, mainly due to the handling costs of the bulk of the material. It suggests that any increase in roof insulation level beyond 150 mm would not be cost-effective in U.K. housing.

Both steps in increasing wall insulation seem to be equally cost-effective with payback times of around six years. Although the insulation increase from 50 mm to 100 mm saves less energy than the increase from 0 to 50 mm, the cost is less. As explained above, this is due to the basic fixing and handling costs of the insulation being included in the first step. The marginal insulation costs above this basic level would be even smaller were it not for the need to pay for the extra bricks and roof area in widening the cavity from 50 mm to 100 mm. Given the large total energy saving due to wall insulation ( £85.6/yr) it would perhaps seem desirable to include even more wall insulation in future house designs. As the Building Regulations stand, though, beyond a cavity width of 100 mm, both leaves of the wall have to be self-supporting. This would introduce a considerable extra cost step.

Floor edge insulation appears to be very cost-effective, with a payback time of just over five years. Given the high floor heat losses measured in the Linford houses, not apparently due to defective floor insulation, it is likely that full underfloor insulation would also be cost-effective.

This is discussed further under future possibilities.

The passive solar measures have a payback time of just over ten years. This can be considerably improved, though, by reducing costs, which have just been taken to be the extra costs of the thermal mass incorporated to prevent summer overheating. This is discussed in section 7.9.

It is also interesting to compare the ranked energy savings for the project with those originally estimated for a Pennyland type house in 1977. The two plots are shown in figures 7.3 and 7.4. Conveniently inflation has given an increase in the index of construction costs of almost exactly a factor of two over the period between 1977 and the cost date for the prices in this chapter, March 1984.

The main differences between the two graphs are:-

1. The inclusion of extra items, such as boiler efficiency, reduced air infiltration and marginal solar savings, none of which could be properly quantified in 1977.

2. A considerable reduction in insulation costs, the most marked being that of the double glazing. Heating system savings have not been included in the 1977 graph, but these only make a difference of about 15% to effective insulation costs.

The 1977 estimates were calculated on a crude degree-day model basis that a reduction in house heat loss of 1 W/$^{o}$C will save 40 kWh/yr of useful space heating. The results from the NBSLD modelling give a higher figure of about 60 kWh/yr.

## 7.8. Future Possibilities

As a result of the measurements on the Linford houses four possible areas for immediate improvements to the energy performance are apparent:-

1. Further increases in boiler efficiency.
2. Extra hot water cylinder insulation.
3. Full underfloor insulation.
4. Optimising the passive solar cost-effectiveness.

As explained above, the Linford houses were equipped with an oversize boiler because of the lack of availability of the correct size at the time of construction. Although the costs have been calculated using the correct size of boiler, it is also likely that this would lead to improvements in boiler efficiency and further fuel savings, not yet taken into account. As calculated in chapter 6, these amount to a further 723 kWh/yr of delivered energy or £8.2/yr.

The losses from the hot water cylinder, estimated to be 3 kWh/day, could be simply reduced by adding further tank insulation, saving a further £3.8/yr for an extra cost of £10.

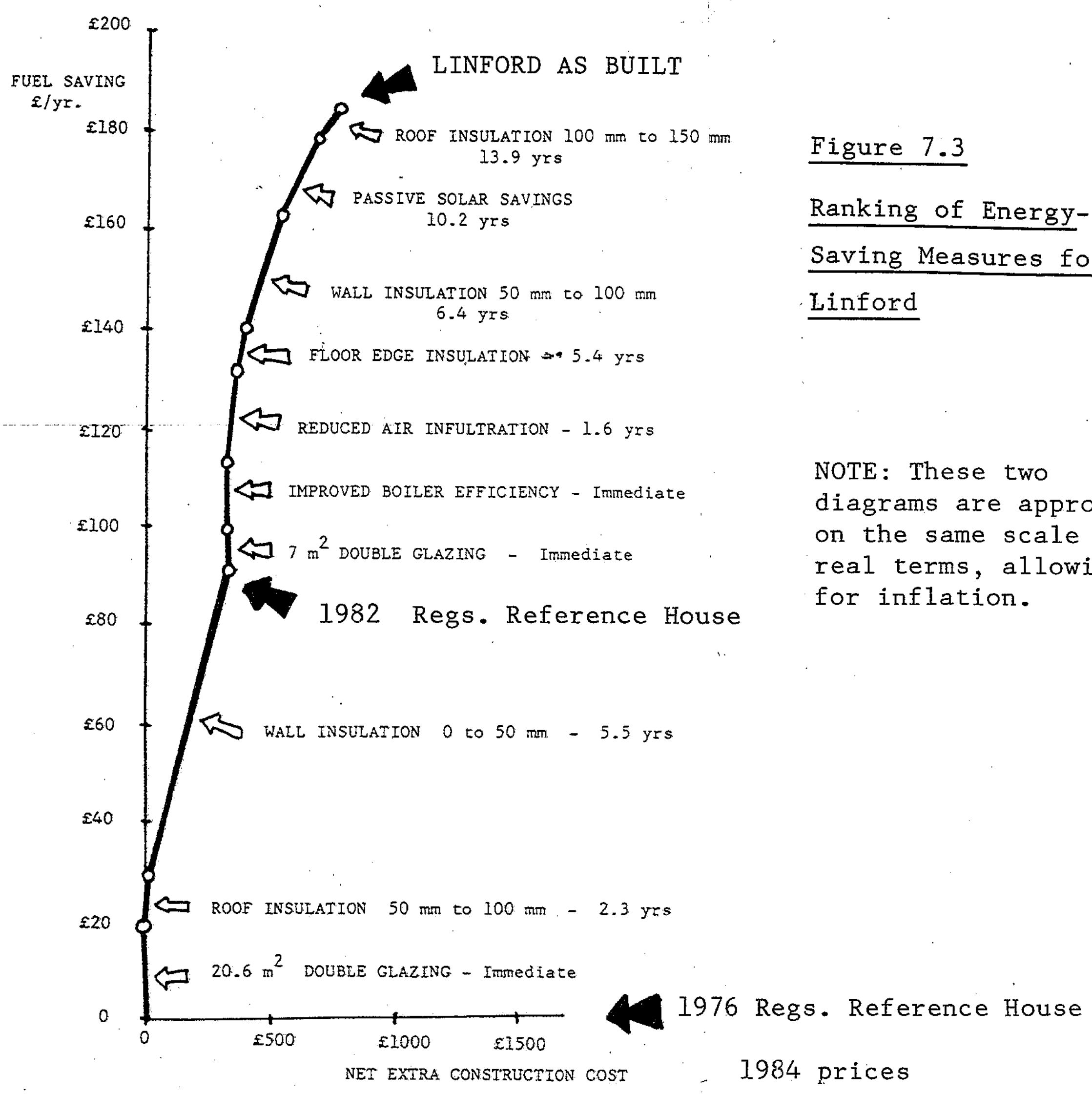



Figure 7.3

Ranking of Energy-Saving Measures for Linford

NOTE: These two diagrams are approximately on the same scale in real terms, allowing for inflation.

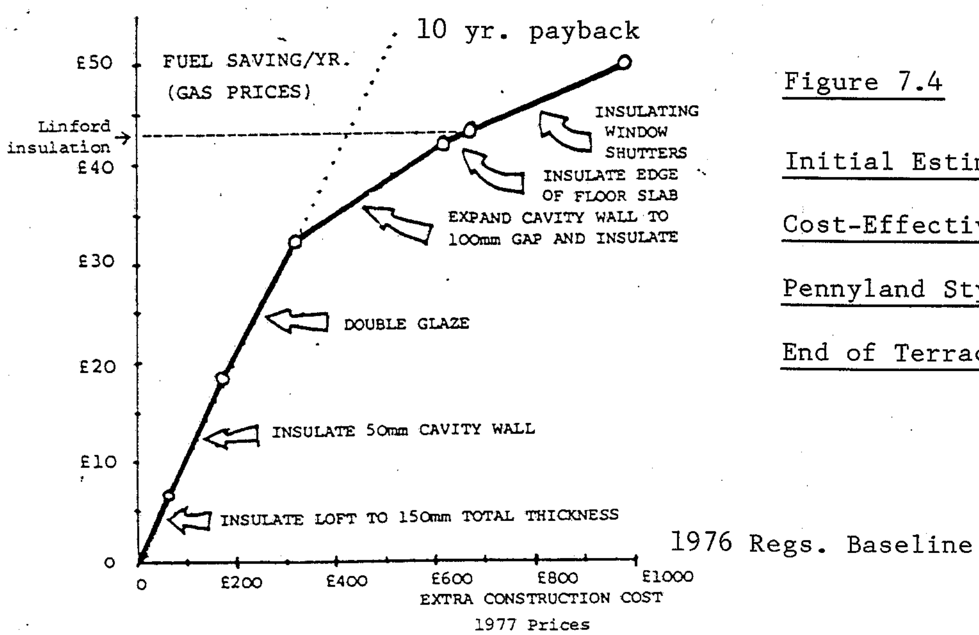



Figure 7.4

Initial Estimates of Cost-Effectiveness Pennyland Style End of Terrace House

Full underfloor insulation potentially would give appreciable energy savings amounting to a further £14.5/yr. An insulation cost of £3/$m^2$ has been assumed, though against this should be set the £53 already spent on edge insulation. This gives a net extra cost of £118.

The total cost and energy savings of these extra boiler and insulation measures are shown in Table 7.7 below:-

Table 7.7 Future Possibilities

| Measure | Delivered Fuel Saving kWh/yr | Fuel Cost Saving £/yr. | Extra Cost £ | Payback Time yrs |
|---|---|---|---|---|
| Smaller Boiler | 723 | 8.2 | 0 | 0 |
| Extra Hot Water Cylinder Insulation | 328 | 3.8 | 10 | 2.6 |
| Full Underfloor Insulation | 1274 | 14.5 | 118 | 8.1 |
| Total | 2325 | 26.5 | 128 | 4.8 |

This clearly demonstrates that the potential for further energy saving has not been exhausted in the Linford design. There are still appreciable energy savings that can be made at minimal extra cost.

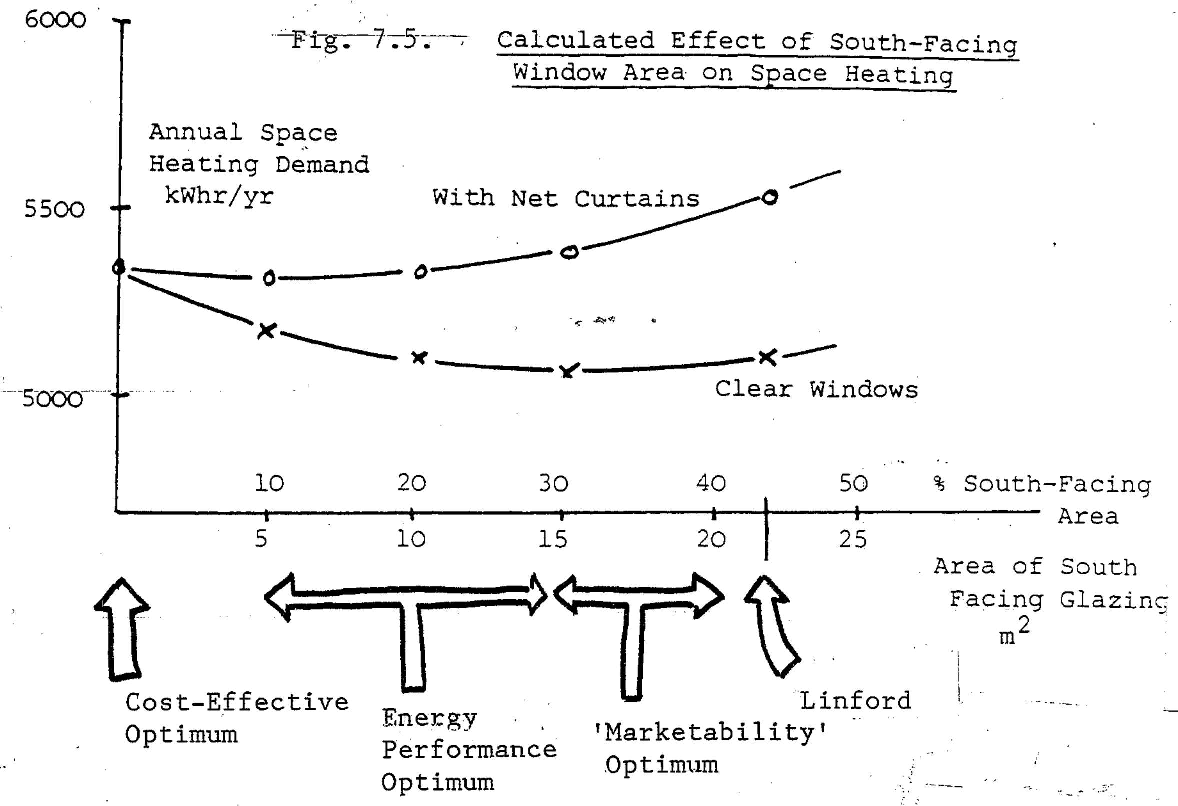
## 7.9. Optimising the Solar Performance

Finally, the cost-effectiveness of the passive solar measures can be improved. The window area chosen for the Linford houses does not represent a performance optimum in the light of the measurements on the test house, as described in chapter 10. Figure 7.5 shows the calculated space heating demand as a function of south-facing window area for the Linford design. This shows that, dependent on the level of window clutter, the space heating demand is largely independent of window area over the range 5-20 $m^2$. The Linford south-facing area of 21.7 $m^2$ is close to the optimum for uncluttered windows, but is on the high side.

Since windows, on average, cost about £60/$m^2$ more than wall (see Table 7.1) the ruthless pursuit of cost-effectiveness leads to a paradox. The most cost-effective house design is that with zero window area! This is obviously not a very habitable house design.

This paradox can only be resolved by reference to the marketability of the house. Although the 1982 Regulations would limit the area of single glazing for a house of the size of the Linford ones to a total of 17 $m^2$, in practice developers are prepared to install a larger area, despite

~~Fig. 7.5.~~ Calculated Effect of South-Facing Window Area on Space Heating



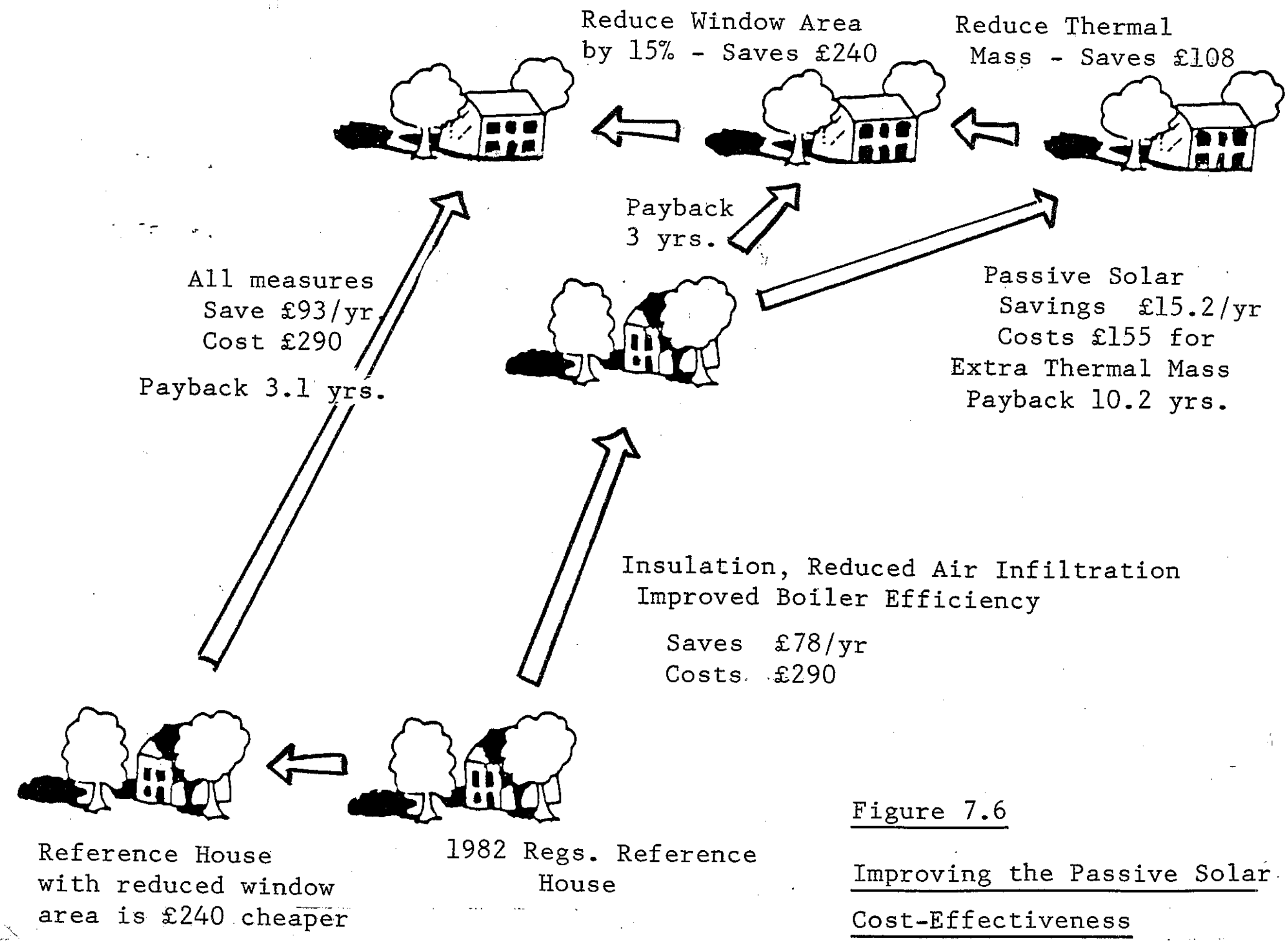




Figure 7.6

Improving the Passive Solar Cost-Effectiveness the necessary extra insulation costs, in order to build a more acceptable house. A survey of current developments similar in size to Linford showed typical total window areas in the range 22-25 $m^2$.

Thus reducing the total window area of the Linford house design by four square metres would bring it into line with what might be called a 'marketability optimum' house design. Removing one square metre from the north side and three from the south would have several beneficial effects:-

1. It would reduce the construction cost by £240
2. It saves a small extra amount of energy, about £1.1/yr.
3. It would reduce summer overheating slightly.

Although the total energy demand for the house would be about the same, the marginal passive solar gains would have been reduced by the proportion of glazing removed, about 15%. The house would be less 'solar' and more 'insulated'.

The reduction of summer overheating problems would be beneficial in enabling thermal mass to be removed from the house. The relatively long payback time for the passive solar measures is critically dependent on the cost of the thermal mass. Given that the measured summer temperatures have not been excessive and that the solar gains do not appear to penetrate to the north side of the house (see chapter 10), it seems possible to remove the thermal mass from much of the structure. Indeed, measurements on the Neath Hill estate, constructed with normal lightweight blockwork, suggest that it might be possible to remove all of it without incurring excessive summer overheating.

It would be very desirable to remove the dense concrete blockwork from the inner leaf of the external walls, since it actually increases the wall U-value and the total heat loss of the house. Doing this would save about £3/yr in fuel costs (this effect is even more serious at lower insulation levels). Since the disbenefits of thermal mass are accounted for under passive solar savings, reducing the thermal mass has the paradoxical effect of increasing the solar contribution.

The extra passive solar saving due to removing the thermal mass is approximately the same as the amount lost by the 15% reduction in total window area, making little total change. It does have, though a drastic effect on the passive solar cost-effectiveness. Restricting the dense blockwork to just the internal partition walls, where suitably supported, would cut the costs by a factor of three, from £155 to £47. This would reduce the passive solar payback time from ten years to just over three.

These improvements in solar performance are illustrated in figure 7.6. Since the choice of reference house is rather arbitrary, it is not really fair to claim the £240 cost reduction for the reduced window area as an 'improvement', rather the passive solar comparison should be made with a revised reference house, also with 4 $m^2$ window area removed (there are also slight energy adjustments to be made for this).

## 7.10. Marketability

To gauge the likely marketability of such houses, discussions have been held with Johnsons, the estate agent for these houses, as well as S + S Homes the builders and Taylors, another estate agency with experience in selling houses with energy saving measures.

The eight houses, which were completed in summer 1981, are detached and were sold for £38,000 on average. This was about the market price for comparable houses, and no special allowance or price increase was made for the energy saving features. The houses were slow to sell, partly because the market was slow at the time, and partly because these higher priced houses were surrounded by lower priced houses, which the selling estate agent felt made them more difficult to sell. Their feeling was that the energy saving extras made them no more difficult or easy to sell. The contractor agreed that they were difficult to sell.

There was general agreement that low energy features are now beginning to have an effect on selling - thus the selling estate agent: "every year that goes by, people get more interested in fuel bills". However, the degree of knowledge is still low. To quote the selling estate agent: "people still don't understand how insulation works" and the other estate agent, "they don't understand the bits - for instance, the draughtstripping that keeps the cold out and the warmth in".

All three were asked about what measures they felt would help to sell houses now. In order of preference all put double glazing first followed by wall, roof and floor insulation. Orientation with simple solar measures was the next most important for both selling estate agent and the other estate agent and also in the personal opinion of the contractor, although his firm did not consider solar orientation in their designs. Finally, draughtstripping was thought to be a useful selling feature, whereas a more efficient boiler was not regarded as important. From this limited evidence solar considerations appear surprisingly high.

The contractor was concerned at the scoring of the glass caused by grit trapped between the two panes of the sashless windows, and its effect on marketability, but he felt that the other measures were satisfactory.

Asked "would Department of Energy independent endorsement of fuel savings figures help in selling houses" all three felt that this would be helpful. However, the selling estate agent felt that the best endorsement of all was statements from the occupants, much more important than any technical report. The contractor felt that fuel comparisons with similar houses with no special conservation measures would be most useful. The other estate agent felt a mixture of the official or third party endorsement coupled with 'the happy punter's view' would be the ideal package.

There also appeared to be a cost threshold, above which the buyer would not feel he was getting value for money. The other estate agent, Taylor's, was quite precise that in starter units the extras had to be less than £750, for people buying up to £39,000 houses the threshold was £1500, and for the top price range it was £2,000-£3,000. The selling estate agent did not differentiate between selling bands, but said that £500-£600 would be acceptable for Linford type measures.

Finally, it is worth mentioning that one developer, Whelmar offer Starter Homes in Milton Keynes with floor, wall and roof insulation and double glazing with draughtstripping, but with a gas fire and no central heating, for the same price as a house with central heating but without these measures (worth about £750). The Taylors estate agent said that they were slow sellers.

It appears from this evidence that the market was not receptive to houses with conservation measures at the time they were built, but is becoming more interested and is prepared to pay a little more, in the region of £500-£750 in small houses, up to £2,000-£3,000 in large houses. Solar measures were surprisingly high up in the marketability ranking of conservation measures, below double glazing and insulation, but above draughtstripping and more efficient boilers.

## 7.11 Conclusions

1. The package of measures incorporated into the Linford houses has been very cost-effective. When compared to the house design that probably would have been built in their place in 1980, there is an estimated fuel saving of £185/yr for net extra construction cost of £782 (March 1984 prices). This gives an overall payback time of 4.2 yrs.

2. Comparing the Linford houses with the house design that probably would have been built in their place after the 1982 Building Regulation improvements still gives good payback times. There is an estimated fuel saving of £93/yr. for a net extra construction cost of £445, giving a payback time of 4.8 years.

3. The cost-effectiveness of the solar measures is potentially high. As built, the Linford houses incorporate a large amount of extra thermal mass, costing £155/house, which must be set against the estimated energy savings of £15.2/yr. This gives a payback time of just over ten years. The thermal mass was incorporated solely to restrict summer overheating and the large amount reflects the desire of the researchers not to produce an uninhabitable house. In the light of measurements, it would seem possible to remove much of the thermal mass, reducing the extra costs and improving the solar payback time to three years or better.

4. The cost-effectiveness of the insulation measures has been very good. The improvements to the Linford house over the 1982 Building Regulation standards are estimated to have saved £45.5/yr for a net extra cost of £259, giving a payback time of 5.7 years.

5. Since the extra energy saving costs are a minute fraction of the total construction cost, even small changes in specification can have large effects on cost-effectiveness. Given that windows are at least twice as expensive per unit area as wall, larger window areas than necessary are difficult to justify, unless technological improvements can drastically alter performance. In the short term, the conclusions must be that it is cost-effective to redistribute glazing and orient the house correctly, avoiding overshading, but not to increase glass area beyond that which would normally be built, in this case a total of 20 - 25 $m^2$ gross window area.

6. The Sashless double glazing has been exceedingly cost-effective. Except in the smallest unit sizes, it costs no more than single glazing. Although there have been some problems of scratching on these windows, this has to be weighed against the cost saving of about £20/$m^2$ over conventional double glazing. It would seem that some of the defects could be cured with minor redesign.

7. The use of a low thermal capacity boiler with a balanced flue has been highly cost-effective, saving £13.7/yr for no extra capital cost. It is likely that even larger savings could have been acheived had a more suitable sized boiler been available at the time of construction.

8. Reducing the air infiltration rate has saved about £19/yr. It is difficult to put an actual cost to this, since in part it is an extra benefit of the double glazing and the use of a balanced flue boiler. The only really visible extra cost is that of draught-stripping the three external doors, a sum of £31.

9. Cavity wall insulation, using glass fibre batts has been very cost-effective, both in the step from 0 to 50 mm thickness and increasing from 50 mm to 100 mm. Both steps have payback times of about 6 years. Increasing the level beyond 100 mm would potentially seem worthwhile were it not for the fact that the Building Regulations require the inner and outer leaves of the wall to be self-supporting beyond this thickness.

10. Floor insulation seems potentially very worthwhile, especially given the site conditions at Linford. It is difficult to put an accurate payback time to this, given the lack of basic research information, but it is likely that full underfloor insulation would pay back in well under ten years. This is an area that needs further research.

11. The increase in roof insulation from 100 mm to 150 mm thickness is far less cost-effective than the step from 50 mm to 100 mm. This is due to decreasing benefits and large extra costs. Although improvements in loft insulation performance could be made by laying insulation over rather than between the joists, it is unlikely that an increase in thickness beyond 150 mm would be cost-effective in the U.K.

12. From a marketing point of view, there is evidence that conservation measures are beginning to be considered by house buyers, although there was little or no benefit obtained by the developers when the Linford house were sold.

13. Solar measures were ranked surprisingly highly by the selling agent, contractor and another estate agent with experience of selling low energy design. All three ranked simple direct gain measures as a more important market feature than draught sealing or efficient boiler, although they also rated it a lower selling feature than double glazing or better insulated fabric measures. This conclusion is tentative, because they were answering questions from someone who was involved in the project and they may have biased their feelings accordingly. However, the unanimity of all three gives support to their evidence.

14. There was some indication of the cost limits, above which buyers would feel that a package of conservation measures was not worthwhile. The figures vary with the size of house, with £500-£600 a target for starter houses, up to £1500 for medium priced houses of around £39,000, and £2,000-£3,000 for top priced houses. These are tentative, based on discussions with the selling agent and estate agent.

15. Figures which were endorsed by the Department of Energy would be a useful selling feature, but the most important feature would be statements by satisfied occupants.

16. The developer, selling agent and estate agent all made the point that there was a great deal of ignorance about energy saving in the market, but people were becoming more knowledgeable and consequently energy conservation features were becoming more described and saleable. This trend was likely to continue, and should be encouraged by providing better information to as wide an audience as possible.

# 8. FABRIC HEAT LOSSES

CONTENTS



This chapter is concerned mainly with the thermal performance of the house insulation. Best estimates are made of the heat losses through individual structural elements, based on a combination of direct measurements, correlation analysis and thermographic studies. These estimates are compared with those made at the design stage.

# 8. FABRIC HEAT LOSSES

## 8.1. Introduction

This chapter is mainly about the house insulation performance, which, as explained in Chapter 6, accounts for well over a half of the project energy savings.

None of the insulation measures can be described as particularly revolutionary and so a detailed determination of the fabric loss was not really envisaged in the project. In practice it has been necessary in order to give accurate estimates of the solar gains.

### 8.1.1. Expected losses

Table 8.1 below gives a breakdown of the initially expected house heat losses. U-values have been calculated from CIBS Guide values of material properties with no allowance for cold bridging. The conductivity of glass fibre insulation has been taken as 0.033 W/m°C. The ventilation rate of 1 ac/hr can only be described as pure guesswork given the lack of information available at the design stage.

Table 8.1. Initially expected heat losses

| Element | Area $m^2$ | (Volume) $(m^3)$ | U-Value $W/m^2\,°C$ | Total Loss W/°C | Percentage of Total |
|---|---|---|---|---|---|
| Walls | 131.7 | | 0.28 | 37 | 15 |
| Floor | 55 | | 0.5 | 27 | 11 |
| Roof | 55 | | 0.21 | 12 | 5 |
| Windows | 27.6 | | 2.5 | 69 | 28 |
| Doors | 3.6 | | 3.0 | 11 | 5 |
| Ventilation | | 263 @ lac/h | 0.33 | 87 | 36 |
| | | | | 243 | 100 |

### 8.1.2. Measurement methods

The fabric heat losses have been determined as a result of controlled experiments on the test house alone, though it would seem that the results are representative of the performance of the occupied houses. Three methods of measurement have been used: thermal calibration, giving a figure for the total house heat loss, heat flux measurements, giving spot U-values and an infra-red survey showing the location of specific defects.

Thermal calibration.

This is a quantitative method relating the space heating energy consumption to the whole house inside-outside temperature difference, $\Delta T$, and the incident solar radiation, to give the solar aperture of the house and the total house heat loss, including floor and ventilation losses.

The process used here follows a method suggested by J. Siviour in 1981 but adapted to pay greater attention to solar gains (reference 8.1).

Determination of the fabric heat loss requires a separate estimate of the air infiltration loss, which is continuously varying with wind speed and $\Delta T$ and also the floor heat loss, which has curious dynamic properties.

The house is maintained at as near a constant internal temperature as possible in order to minimise day to day energy storage effects and the problems of the difference between measured air and radiant temperatures.

The house energy balance can be drawn up:

$$Q + R.S = (\Sigma A.U + Cv).\Delta T + F$$

where $Q$ = measured space heating
$R$ = solar aperture of the house
$S$ = south-facing vertical solar radiation
$\Sigma A.U$ = fabric heat loss, walls, windows, roof
$Cv$ = air infiltration rate
$\Delta T$ = house inside-outside temperature difference
$F$ = floor heat loss

The equation can be rearranged as:

$$(Q - F)/\Delta T - Cv = \Sigma A.U - R.S/\Delta T$$

All the terms on the left hand side are measured and by plotting the left hand side of this equation against $S/\Delta T$, we get a graph with a Y-intercept of $\Sigma A.U$ and a slope of $-R$, the solar aperture.

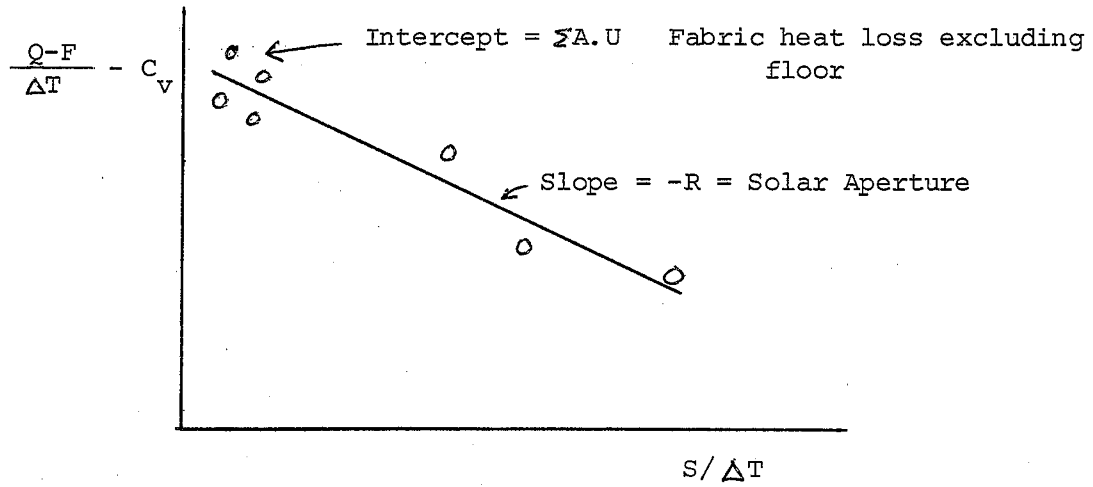



Figure 8.1. Thermal Calibration Plot

In order to get good results it is necessary to have a fair number of points at low values of $S/\Delta T$ (dull cold weather) to fix $\Sigma A.U$, the fabric heat loss, plus a good spread of values of $S/\Delta T$ to determine the solar aperture. Considerations of the availability of suitable weather tend to limit the process to the period October to March and to fairly short timescales, individual datapoints being in the range days to weeks. Most test house calibrations have been carried out on a daily basis, with slight adjustments in the values of $\Delta T$ to compensate for thermal timelags in the building fabric. The topic of timescales and the thermal calibration process in general is described in greater detail in a further O.U. report in the near future.

Spot heat flux measurements

Heat flux sensors were embedded in the external fabric of the house in four positions:

(i) The underside of the loft insulation

(ii) The inside surface of the living room exterior wall

(iii) The top surface of the ground floor slab, about 0.6 m from the edge

(iv) The top surface of the ground floor slab, about 2 m from the edge.

These sensors have allowed spot estimates of the U-values of the roof and wall insulation. The floor sensors have allowed an estimate of the total house floor loss, albeit extrapolated from only two spot measurements in the same corner of the house.

Thermographic survey

Checks with an infra-red camera have allowed a qualitative assessment of the insulation in the test house. As the photographs in this chapter show, it is very easy to pinpoint insulation defects and check that the heat flux sensors are not positioned in the middle of any thermal anomalies.

8.1.3. Measurement errors

The thermal calibration process can determine the <u>total</u> house heat loss fairly accurately, with typical errors of ±5%, mainly due to errors in temperature measurement.

The disaggregation into separate components, though, is rather imprecise because of the larger experimental errors involved.

Air infiltration measurements as made with the O.U. rig described in Chapter 9 are likely to have typical errors ±20% or more.

The empirical equation relating air infiltration to wind speed, direction and $\Delta T$, which was used for most of the thermal calibration experiments has errors of 30-40%. This is equivalent to about ±10 W/°C.

The two heat flux sensors embedded in the floor have also proved somewhat inadequate for the calculation of the total floor loss since (a) they are both situated in the same corner of the house and (b) they have also been used to monitor the considerable daily flows of solar energy into and out of the floor slab.

Generally, where there have been conflicts over the use of sensors or particular experiments for heat loss purposes or for solar gain purposes, they have been resolved in the solar direction.

Taking into account the calibration errors of the heat flux sensors and the difficulty in separating out the effects of solar radiation, it is unlikely that the floor heat loss can be specified to better than ±25% or about 10 W/°C.

Any figure for the house fabric heat loss excluding the floor thus has to include all these experimental errors (though fortunately they add as the square root of sums of squares) and should thus be given fairly generous error bars of ±20 W/°C.

## 8.2. Wall Heat Loss

The external walls are insulated with 100mm fibreglass batts, with an assumed U-value of 0.033 W/m°C giving an expected U-value of 0.28 W/m² °C. Measurements with a heat flux sensor embedded in the inside surface of the living room wall suggest a U-value of 0.25-0.3 W/m² °C (see Figure 8.2). The results are slightly confused by what appears to be a large zero offset error. This may be due to a monitoring fault (considerable trouble was experienced with mains hum problems) or, more likely, the effects of the sun shining on the exterior surface of the wall. Either way, it is unlikely that the spot U-value exceeds 0.35 W/m² °C.

The thermographic survey showed that this sensor was situated in the centre of a batt of insulation. The edge of the batt was just visible from the interior, with a local surface temperature about 2°C below that of the rest of the wall. It was hardly visible at all from the outside.

In general the standard of wall insulation appeared good, the only obvious defects being a slight slippage of insulation under the kitchen window [see Figure 8.5.6(b)] and a larger patch between the house and the garage which is probably associated with the monitoring equipment cables.

The evenness of the wall insulation at Linford is in marked contrast to measurements at Pennyland where a mottled heat flow through the walls showed the uneven insulation thickness, especially in the Area 1 houses, having only 50mm insulation.

Taking the assumed average U-value of 0.28 W/m² °C and adding 5 W/°C for cold bridging due to lintels, the total wall heat loss is likely to be about 42 W/°C or 22% of the total house heat loss.

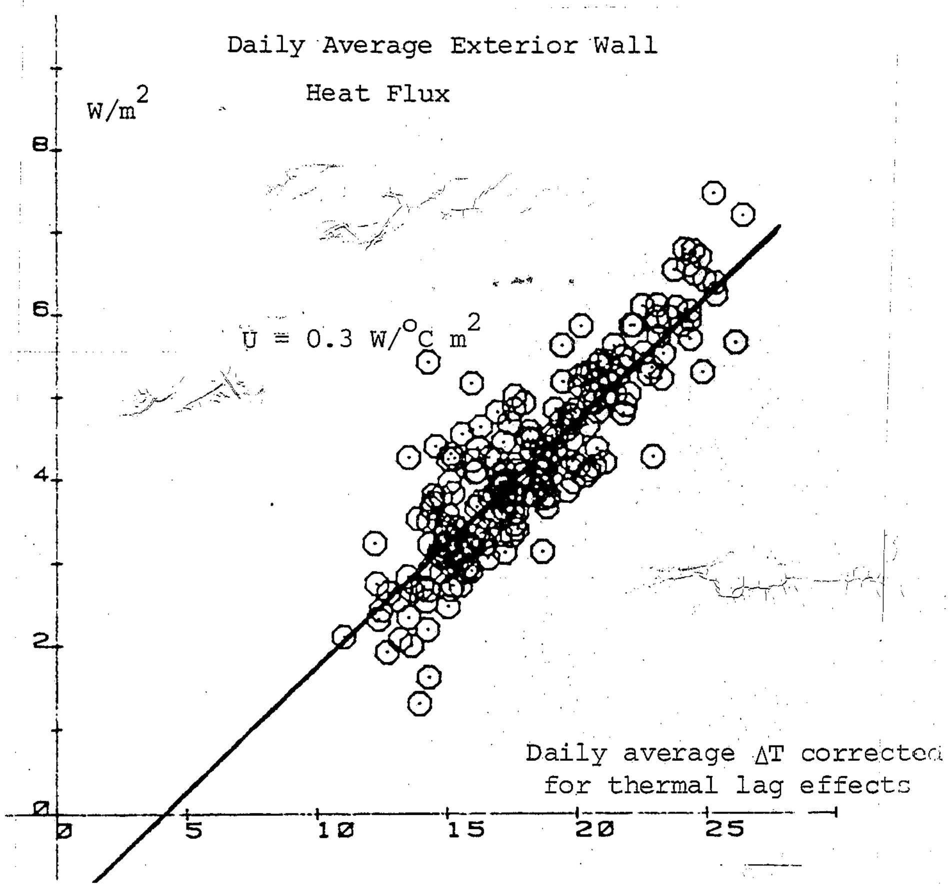



Figure 8.2. Wall U-value

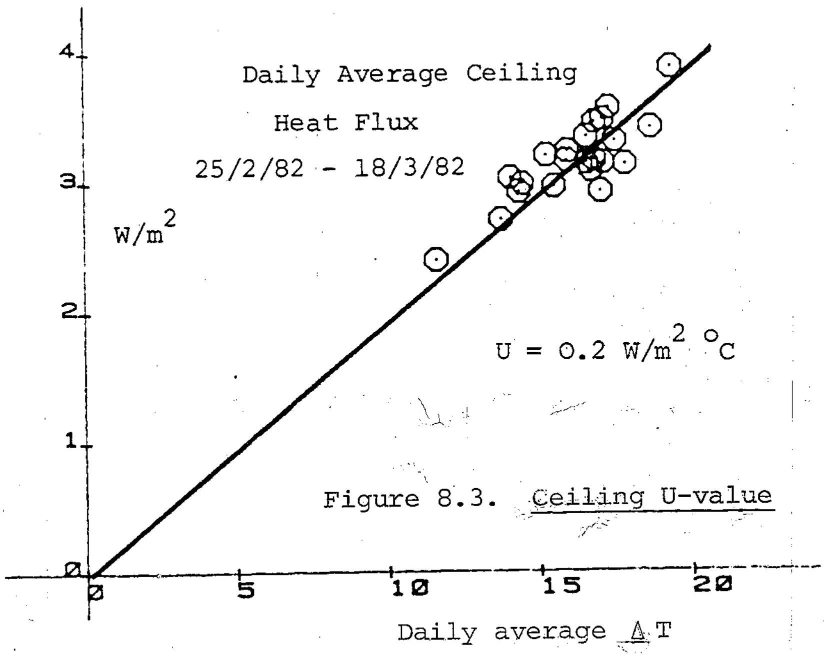



Figure 8.3. Ceiling U-value

## 8.3. Roof Heat Loss

The loft floor was insulated with rolls of 140 mm fibreglass insulation laid in a single thickness between the joists in a normal manner. This thickness should give a U-value of 0.21 W/m² °C and a total roof heat loss of about 11 W/°C ignoring cold bridging effects.

The U-value was confirmed by measurements with a heat flux sensor set into the plasterboard ceiling beneath the centre of a roll of insulation (see Figure 8.3).

Thermographic measurements were not so encouraging. Cold bridging following the lines of the joists could be clearly seen from below [Figure 8.4(a) and (b)] and heat could be seen rising into the loft space from above. The main problem appeared to be that the insulation was not pressed down firmly against the sides of the joists, allowing air circulation and heat loss. The only insulation actually missing was a small portion where the fibreglass had not been pushed under a transverse tie bar used to support the roof truss during construction. Approximately 10% of the roof area suffered from cold bridging defects and it is likely that the final roof heat loss is about 15 W/°C or about 7% of the total house heat loss.

The quality of installation could possibly be improved by using two layers of insulation, one laid between the joists and another transversely over the top.

## 8.4. Window and Door Heat Loss

There is not a lot that can be said about the windows themselves. Having thick wooden frames and a large air gap between the panes, they are probably very thermally efficient, with a likely U-value of about 2.5 W/m² °C as given in the CIBS Guide. Checking this value was beyond the scope of this project.

Assuming the value to be true then the total window heat loss is 69 W/°C or 32% of the total house heat loss.

It is possible to comment on the thermal properties of the window surround details from the thermographic survey. This is quite important, since it is not much use preaching the passive solar benefits of large windows if this also means introducing numerous cold bridges associated with lintels and window jamb details.

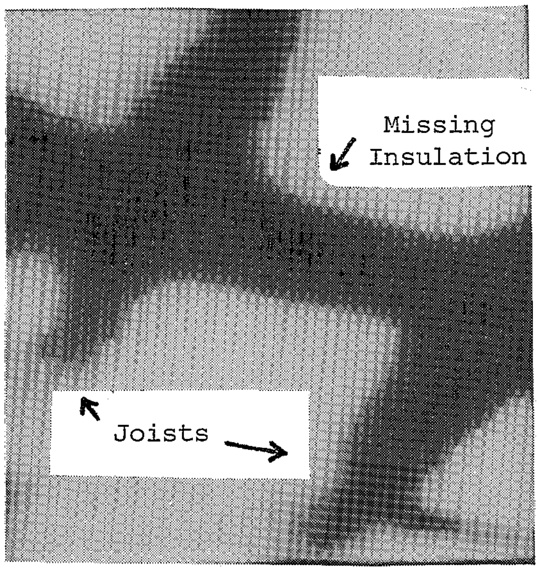
The edge losses were studied with the infra-red camera and in order to cut down interference from the cold glass two windows were blocked off with 50 mm polystyrene insulation and sealed around the edges.

### 8.4.1. Lintels

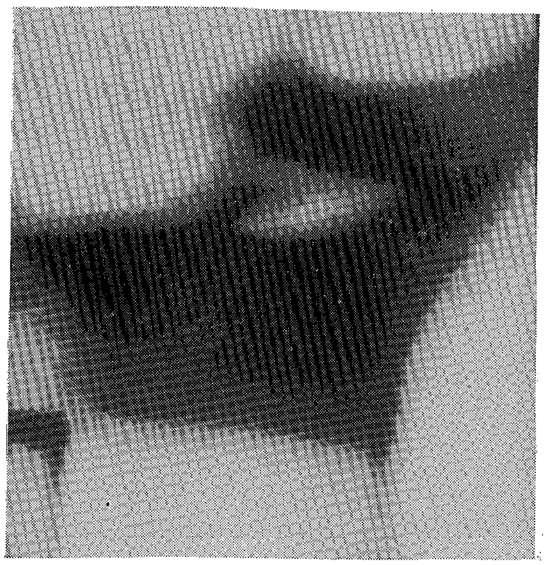
The lintels over the windows are of a hollow box construction, minimising the actual area of the cold bridge, though meaning that it does have a high thermal conductivity (see Figures 8.5 and 8.6). The lintels were clearly

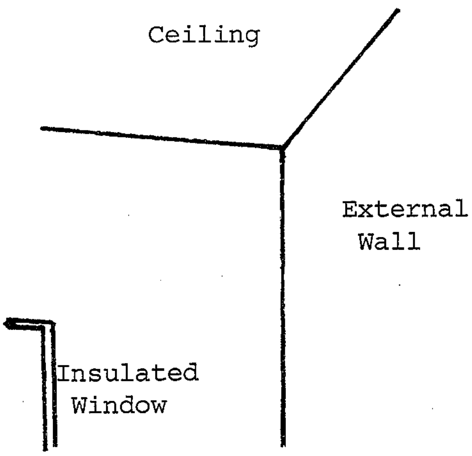
Figure 8.4 Bedroom Ceiling Heat Losses

A.




B.





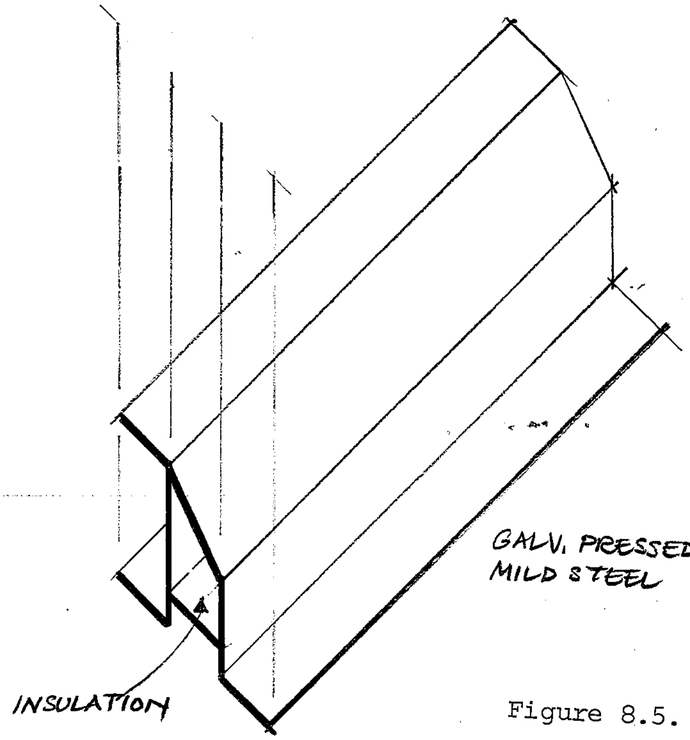



Figure 8.5. Lintel Construction

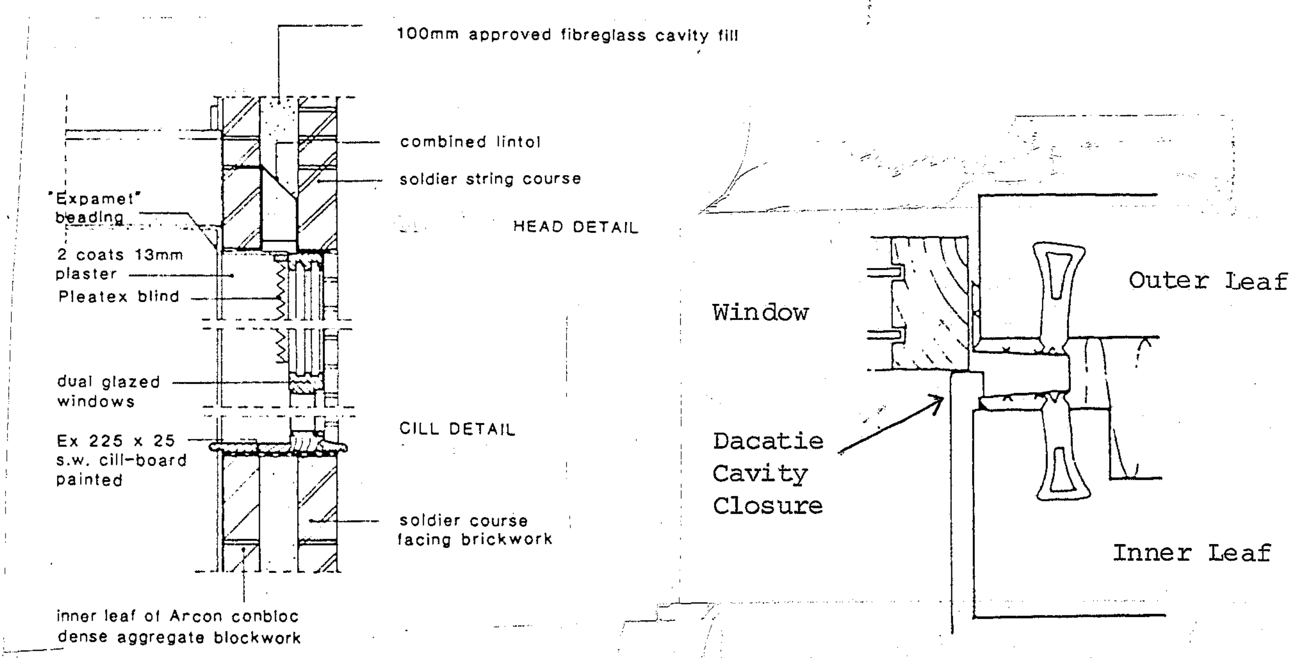



Figure 8.6. Window Detailing

visible in infra-red from both the interior and exterior (Figure 8.8). From the outside there was clearly a thin warm strip of metal running across the top of the windows [especially across the top of the insulated window in Figure 8.8(b)]. On some of the uninsulated windows some of the apparent heat loss may be due to warm air rising up the outside of the glass.

Internally the square structure of the lintel could be seen as a cold patch above the windows.

It is unlikely that this structure could be improved thermally. A split lintel structure is possible but does not fulfill the important function of bonding the inner and outer leaves of the wall.

The sum total extra heat loss due to all the lintels in the house is unlikely to be more than about 5 W/°C or about 2% of the total house heat loss.

### 8.4.2. Window jambs

The window jamb structure did not appear to constitute a cold bridge. This was difficult to observe since it involved getting a good seal of the window insulation against the window surround. Where this could be achieved it was obvious that the wall surface just inside the window was no colder than the rest of the interior wall surface.

### 8.4.3. Window cill

As already mentioned, there did seem to be a slight slippage of insulation under the kitchen window. This appeared to be a fairly common problem during construction, but the extra heat loss given the limited area is probably less than 0.5 W/°C.

### 8.4.4. Ground floor under windows

The short path length through the concrete slab under the ground floor windows could potentially be a serious cold bridge, especially in a floor with no perimeter insulation. In this case the floor perimeter heat loss did not appear any different under the windows from the losses under the thick exterior walls suggesting that the perimeter slab insulation was working.

### 8.4.5. Doors

The front door on the north side is of solid wood construction and has been assigned a U-value of 3.0 W/m$^2$ °C in the initial estimates. However the draught lobby immediately inside the door and its internal door of double plywood skin construction probably reduce the effective composite U-value to around 1.5 W/m$^2$ °C. Similar considerations apply to the kitchen door to the garage with its own lobby. The two north-facing doors thus probably constitute a heat loss of about 6 W/°C or 3% of the total house heat loss.

## 8.5. Floor Heat Loss

The floor heat loss has been one of the most mystifying parts of the project, both as regards the magnitude of the losses and the dynamic mechanisms involved. The lack of literature on the subject at the design stage was taken to mean that there was not very much to know and consequently very little monitoring equipment was devoted to this area. In retrospect it seems a great pity that the level of ignorance was not appreciated. The provision of a few more heat flux sensors and several ground temperature sensors could have made the interpretation of the results a lot easier and added considerably to the rather poor body of knowledge.

### 8.5.1. Construction

The ground floor is of solid concrete construction on hardcore. The floor slab ends inside the external walls (see Figures 8.9 and 8.10) and is insulated with 1 metre width of 25 mm thickness waterproof expanded polystyrene tucked in under the edge. Similar construction was used in the Pennyland Area 2 houses built to the same insulation level and also in the Area 1 houses except that here the edge insulation was omitted.

The local soil is a thick heavy clay forming a fine grade of glutinous mud in winter (the first project expenditure was 10 pairs of wellington boots!).

When it was realised that the magnitude of the floor loss was upsetting the determination of the solar aperture it was decided to temporarily insulate over the whole floor surface with 50 mm polystyrene insulation. This was carried out in December 1983, allowing 6 months measurements on this alternative construction.

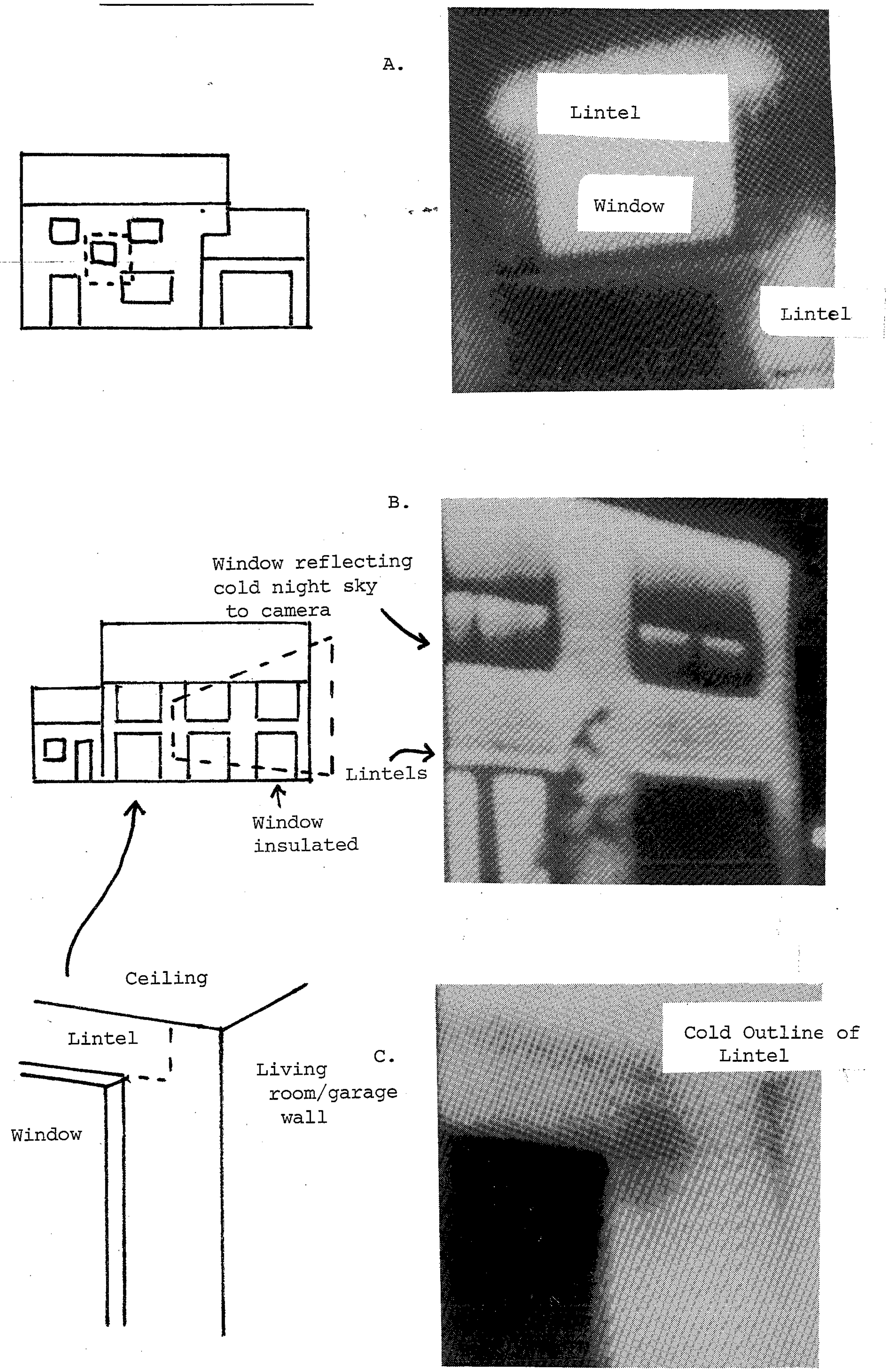
### 8.5.2. Theory and expected losses

The heat losses of solid floors are rather difficult to work out, since the important factor is not the thermal resistance of a relatively thin piece of insulation, but the resistance of a long thermal path down through the soil (which may have quite a high conductivity) and under the walls (see Figure 8.11). The effect of perimeter insulation is to force the heat to take an even longer path through the soil from the house to the outside air.

The normal way of calculating solid floor heat losses is to use the tables in the IHVE and CIBS Guides (References 8.2 and 8.3) of loss as a function of house geometry.

The history and validity of these tables will be discussed in Section 8.7.

Figure 8.8 Lintel Heat Losses



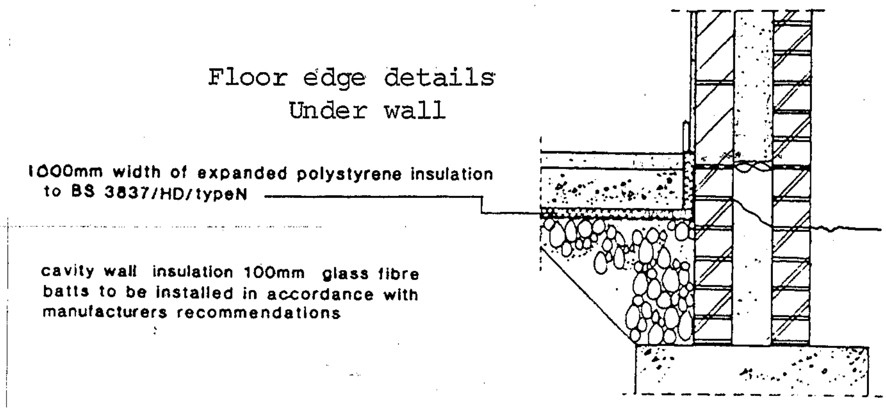
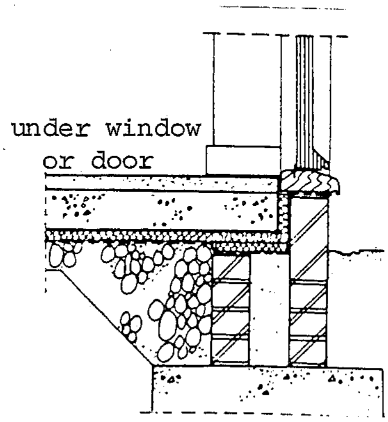


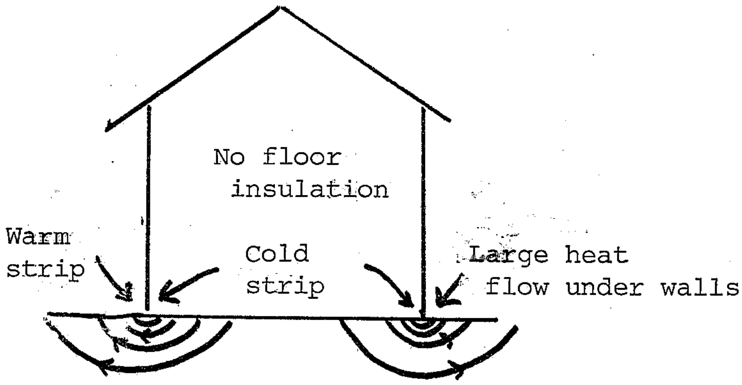

FIG.8.9.




ASSEMBLY DETAILS

FIG.8.10

FIG.8.11.




Effect of edge insulation on floor heat flux

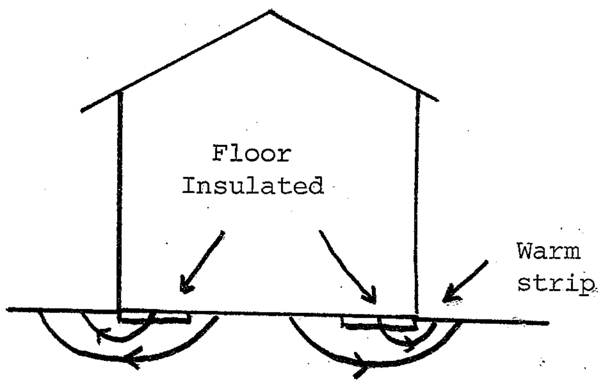


Table 8.5.1. Estimated floor U-values.

| | |
|---|---|
| Tabulated loss of floor 7 m x 7 m (actual dimensions 9 m x 6.3 m) | 0.76 W/m² °C |
| Less allowance of 25% for 1 m edge insulation | 0.57 W/m² °C |
| Less allowance for tiles and carpet | 0.51 W/m² °C |
| Less allowance for 50 mm extra polystyrene insulation | 0.32 W/m² °C |

8.5.3. Measurements

Two heat flux sensors were embedded in the concrete floor surface just inside one of the south-facing windows in the S.E. corner of the test house. These two spot sensor measurements have been extrapolated to produce an estimate for the total floor heat loss. The process is complicated by the fact that the sun actually shines on the floor over the sensors and they have also been used to monitor the considerable solar energy flows into and out of storage in the floor. The separation of the solar effects from the steady state heat loss will be described in Section 8.7.

The simplest statement that we can make about the measured U-value of the floor is to plot daily measured values of floor heat loss against daily average values of house inside-outside temperature difference $\Delta T$ for the periods of the thermal calibration experiments. This is shown for the floor before and after insulation in Figures 8.12 and 8.13. These graphs produce floor U-values of 0.9 and 0.45 W/m² °C respectively, but the very poor fit and totally different nature of the two plots does seriously question the validity of this kind of simplistic thinking. More appropriate ways of expressing the floor loss will be discussed later.

Thermal calibration experiments also cast doubt on the validity of extrapolating from the two sensors to the total floor heat loss for the period after the floor was insulated over. It would seem that a more realistic value for the insulated floor allowing for the considerable cold bridges created by the dense concrete party walls penetrating the insulation would be about 0.7 W/m² °C.

8.5.4. Thermographic survey

This was carried out in November 1983 after the temporary extra floor insulation had been removed.

Infra-red observation of the exterior of the test house clearly showed a warm strip running along the base of the east and north walls. Figure 8.14(b) clearly shows two bicycles illuminated by the infra-red glow of the floor edge behind (the apparent warm patch to the right of this picture is caused by the different emissivity and angle of the house meter cupboard doors).

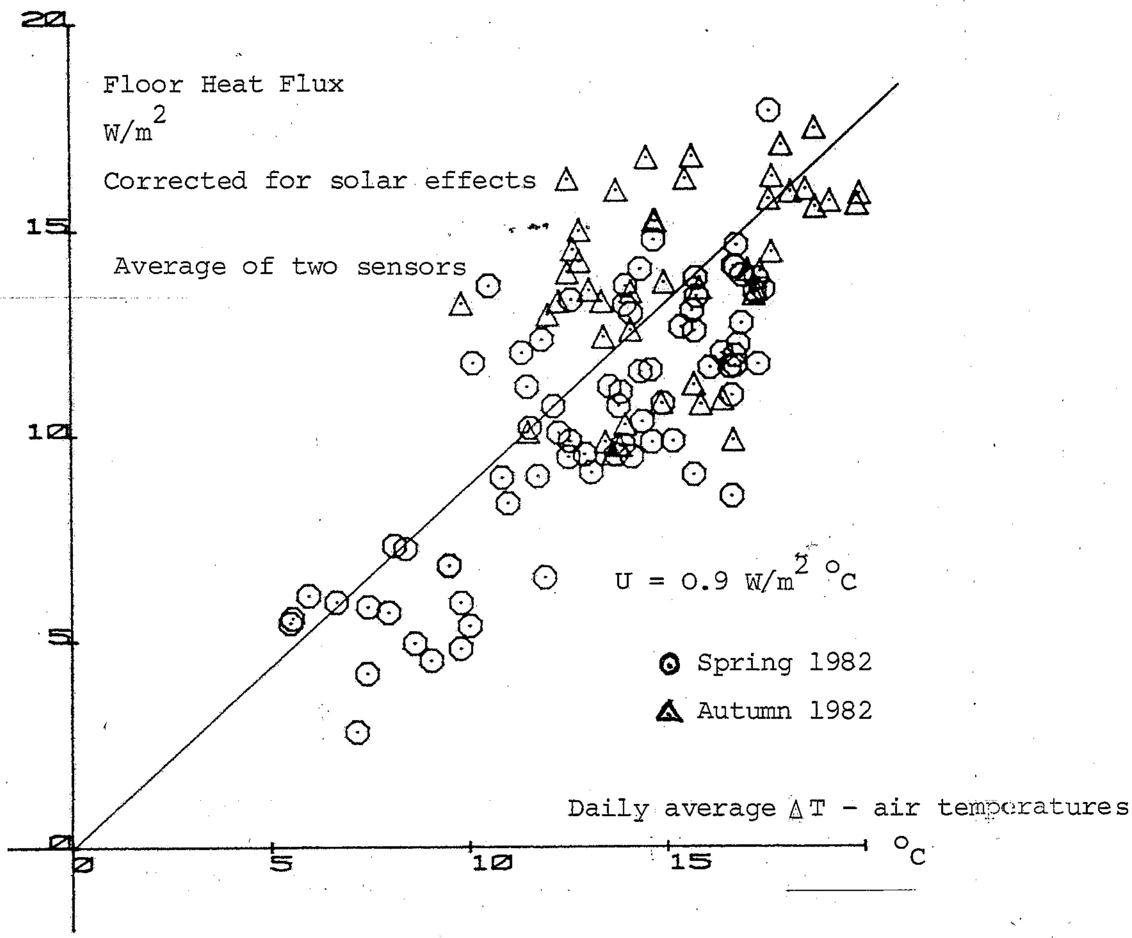



Figure 8. 12. Floor U-value before insulation

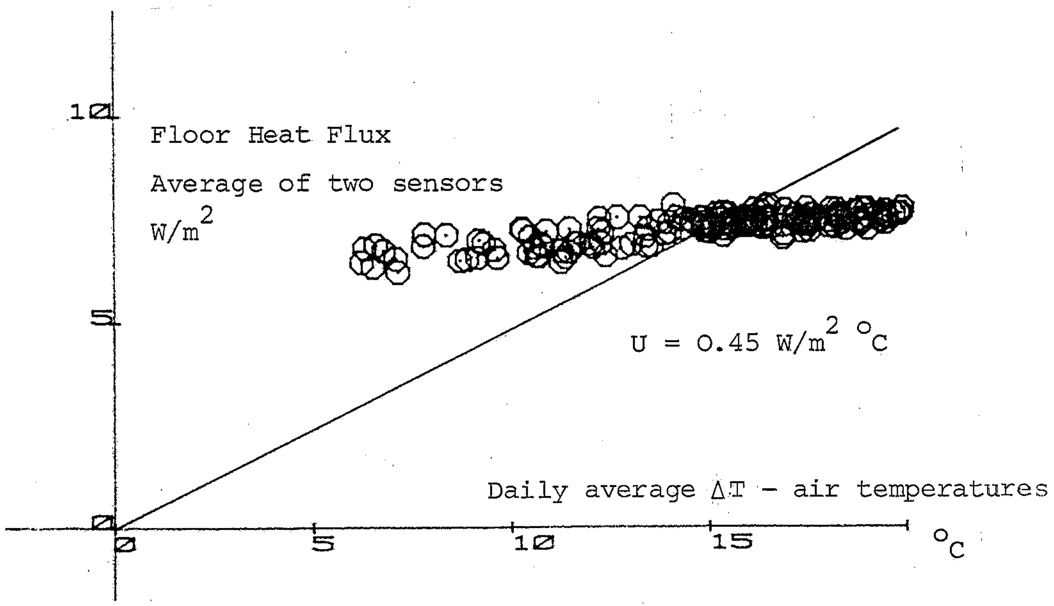
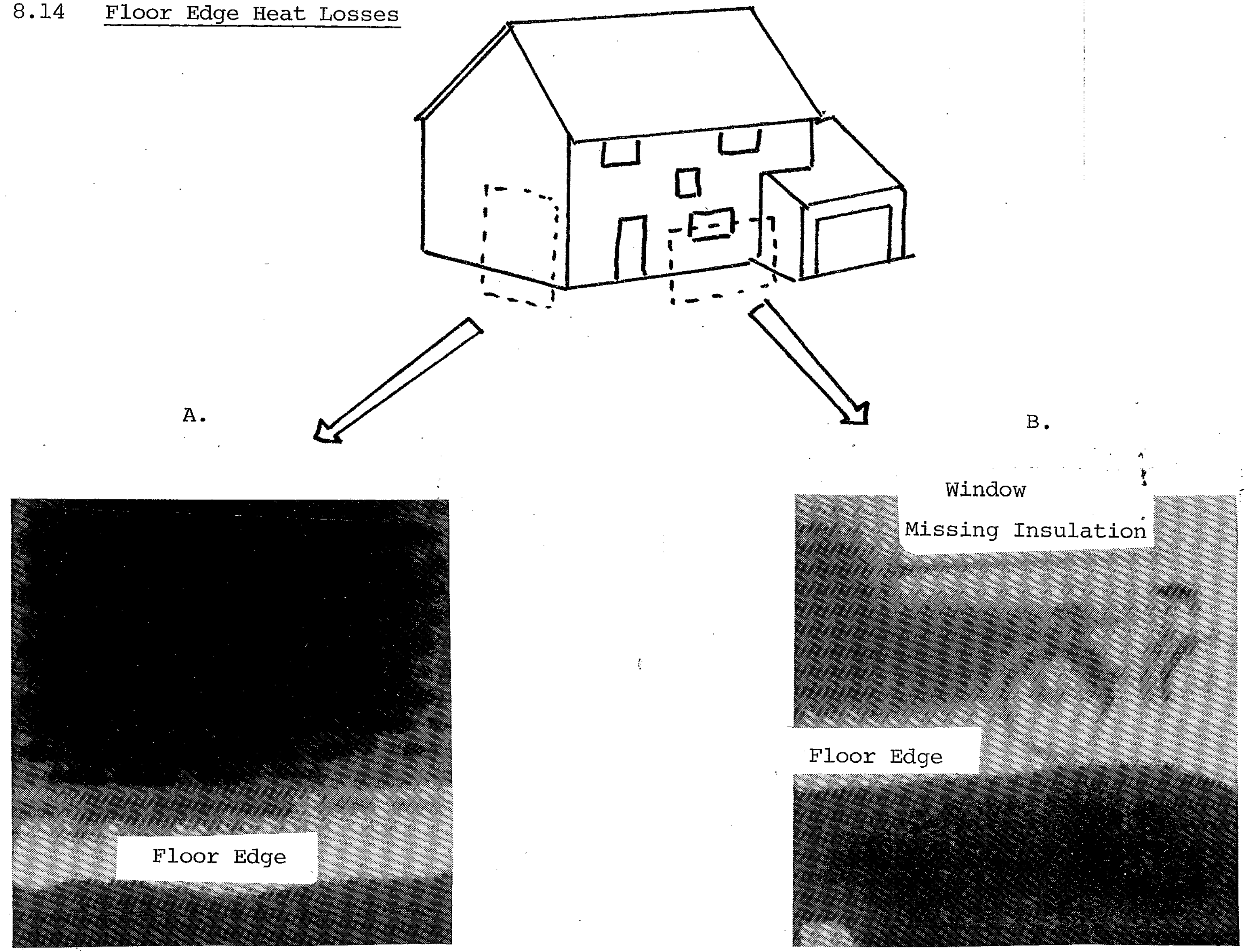



Figure 8.13 . Floor U-value after insulation with 50 mm polystyrene

Figure 8.14 Floor Edge Heat Losses



The floor loss on the south facade was more difficult to see because of the downstairs windows which extend to ground level, but did not seem to be any worse than on the other two walls.

There did not appear to be an equivalent cold perimeter zone inside the house, suggesting that the perimeter insulation was doing its job in forcing the heat flow beneath it (see Figure 8.11). There was no visible variation in interior floor heat loss over the entire area. This suggests that the extrapolation from the two spot sensors to the whole floor loss is not seriously wrong.

The characteristic warm stripe around the base of the building was also observed on the north facades of two occupied Linford houses that were inspected and also on many Pennyland houses (see Figure 8.15). The Pennyland Area 2 houses are constructed with the same style of floor insulation but this was omitted in the Area 1 houses. There appeared to be little visible difference from the exterior, though this difference would be expected to be only about 25% and surrounding vegetation made observations difficult.

By way of comparison a visit was made to another Milton Keynes estate, Beanhill, where floor heat losses had caused sufficient problems for retrofit insulation measures to be made. On this estate the uninsulated floor slab extended unbroken under the exterior walls. Here not only was there a clearly visible warm stripe around the exterior of the house but also a corresponding cold one on the inside of the house.

The effect of the retrofit insulation, approximately 25 mm fitted along the exterior edge of the floor slab, was to make the floor loss undetectable with the infra-red camera from the exterior. Unfortunately it was not possible to check whether the interior cold stripe had also disappeared.

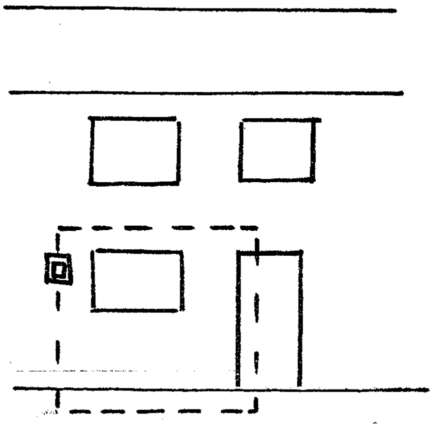
## 8.6. House Total Heat Loss

### 8.6.1. Test house

Thermal calibration experiments were carried out on the test house over the period March 1982 to June 1983 using the method outlined earlier in the chapter. For most of March and April 1982 the test house internal temperature was kept at a constant 22°C and the air infiltration rate was measured continuously. From mid-October 1982 to the end of June 1983 the internal temperature was kept at 25°C. The air infiltration rate was measured intermittently over the period, but mostly has been predicted from the empirical equation relating it to wind speed, direction and measured $\Delta T$ described in the next chapter. These thermal calibration experiments have been used not only to determine the fabric heat loss of the test house, but also to determine the solar aperture with and without net curtains and also to give an estimate for the reduction in heat loss as a result of insulating over the floor.

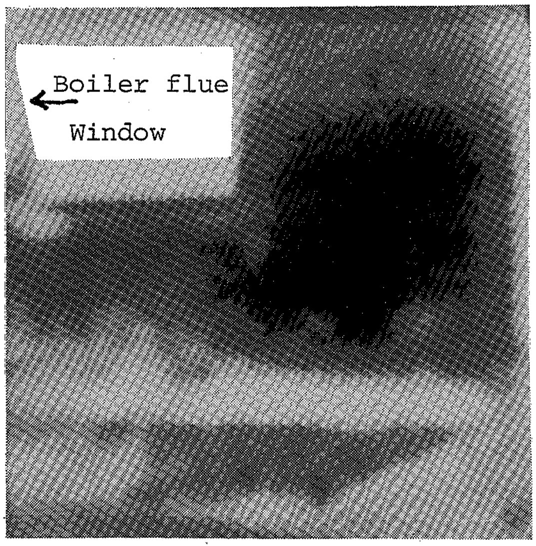
The calibration process can estimate the total house heat loss including floor and infiltration fairly accurately. Getting the best estimate for the heat loss of the house excluding these two components depends on getting good estimates for the total loss, the floor loss and the infiltration loss all at the same time. It is likely that the estimates of floor heat loss

Figure 8.15 Pennyland Floor Edge Heat Losses




Area 1

No edge insulation




Area 2

Edge insulation as Linford

Figure 8.16 Test House Thermal Calibration

13 days 13/3/82 to 25/3/82

$\Sigma U.A = 3.1 \pm 0.1$ kWh/day$^{o}$C
$= \underline{127 \pm 5 \text{ W/}^{o}\text{C}}$

$R = 9.8 \pm 0.6$ $m^2$ (No curtains)

$r^2 = 0.96$

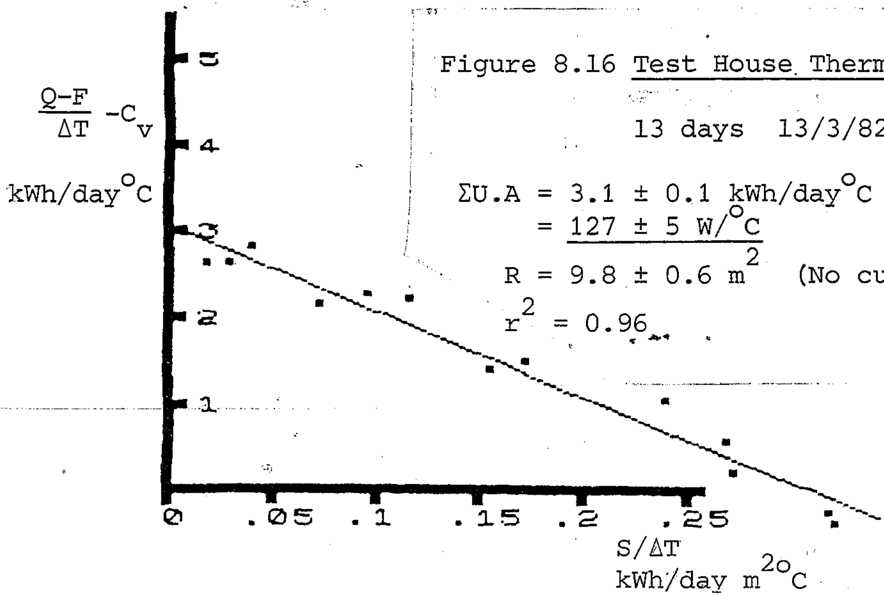


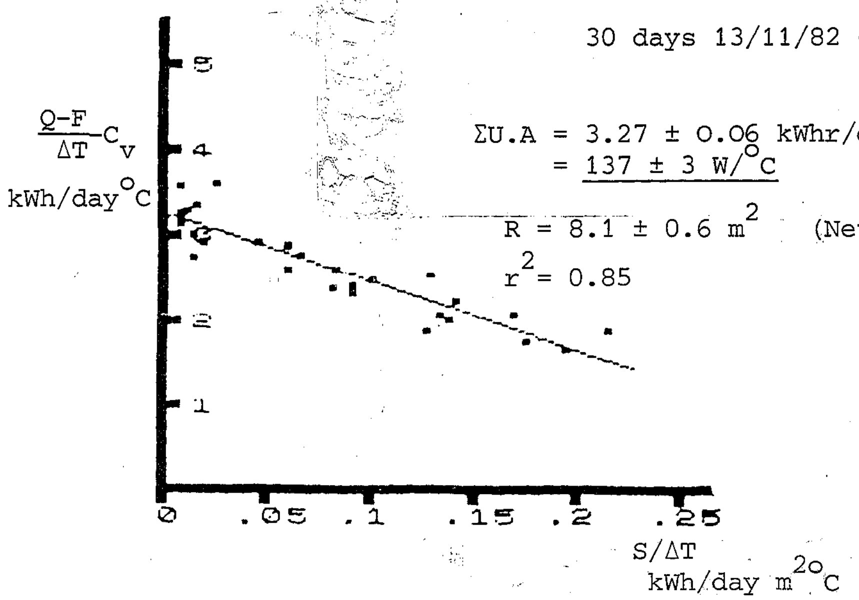

Figure 8.17 Test House Thermal Calibration

30 days 13/11/82 - 12/12/82

$\Sigma U.A = 3.27 \pm 0.06$ kWhr/day$^{o}$C
$= \underline{137 \pm 3 \text{ W/}^{o}\text{C}}$

$R = 8.1 \pm 0.6$ $m^2$ (Net curtains)

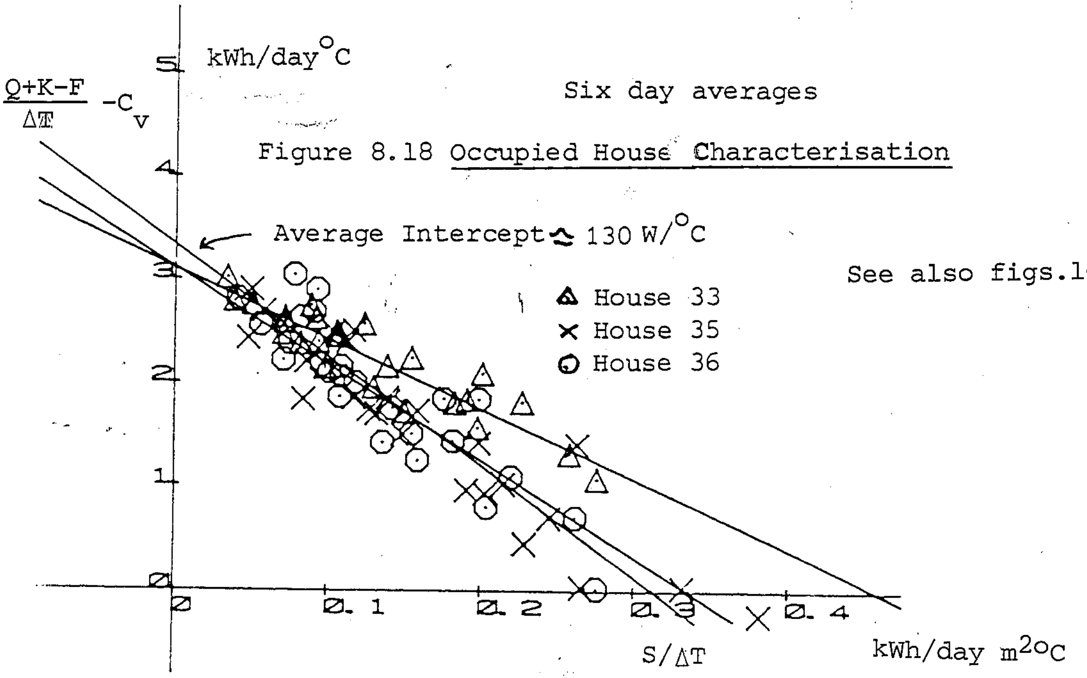
$r^2 = 0.85$




Six day averages

Figure 8.18 Occupied House Characterisation

See also figs.10.24-27



from the two sensors are unreliable after the floor was insulated over in December 1982. The best estimates of fabric heat loss thus come from data in March 1982 (see Figure 8.16) and November-December 1982 (Figure 8.17).

These give figures of 127 and 137 W/°C respectively. The quoted errors on the graphs of 3 and 5 W/°C are merely statements of the quality of fit of the data to a straight line, and do not take into account the considerable extra measurement errors of around ±15 W/°C. Thus the difference in the two estimates is not significant.

### 8.6.2. Occupied houses

The calibration process can be extended to the occupied houses, to demonstrate that they have similar thermal properties to the test house. Here it is necessary to make a considerable number of assumptions.

Free heat gains from cooking, lighting, etc. have to be added to the heating term (see Chapter 11). The floor loss has been calculated from an assumed floor U-value of 0.9 W/m² °C, an assumed sinusoidally varying ground temperature and measured internal house temperatures. The air change rate has been estimated from the empirical equation relating infiltration with wind speed, direction and ΔT developed for the test house, but scaled according to individual pressure tests for the occupied houses and allowing for the measured window opening. This rather complex procedure is described in the next chapter.

Fortunately, after making all these assumptions, graphs for three of the houses, 33, 35 and 36, can be superimposed showing that although they have slightly different solar apertures, corresponding to the degree of window clutter they have very similar fabric heat losses of about 130 W/°C (see Figure 8.18). House 38 showed a slightly higher heat loss nearer 165 W/°C, though the difference may be due to the extensive assumptions rather than any real difference in heat loss.

### 8.6.3. Heat loss breakdown

The final picture is of a fabric heat loss of walls, roof and windows of about 130 ±20 W/°C. We also have a floor heat loss of 50 ±10 W/°C. For the occupied houses there is an estimated typical air infiltration rate (windows closed) of 0.26 ac/h or 22 W/°C plus a ventilation rate (i.e. the effect of opening windows) of an extra 0.06 ac/h or 6 W/°C. This is described in the next chapter.

This breakdown is compared with the initial estimates in Figure 8.6.4 and Table 8.2 below.

Table 8.2. House heat losses

| Element | Expected W/°C | % | Assumed after measurements W/°C | % |
|---|---|---|---|---|
| Walls | 37 | 15 | 42 | 20 |
| Windows | 69 | 28 | 69 | 32 |
| Roof | 12 | 5 | 15 | 7 |
| Doors | 11 | 5 | 6 | 3 |
| Subtotal | 129 | 53 | 132 | 62 |
| Floor | 27 | 11 | 50 | 23 |
| Ventilation | 87 | 36 | 33 | 15 |
| Total | 243 | 100 | 215 | 100 |

The total heat loss of the building is similar to expectations, giving rise to similar energy demand estimates. The breakdown of losses, though, is completely different. The floor loss has risen to be almost a quarter of the total loss and the ventilation loss shrunk to a mere 15%.

The estimate of the heat loss of the walls, roof, windows and doors is largely similar. The extra cold bridging losses of joists and lintels are somewhat offset by the assumed sheltering of the doors by the lobbies and garage.

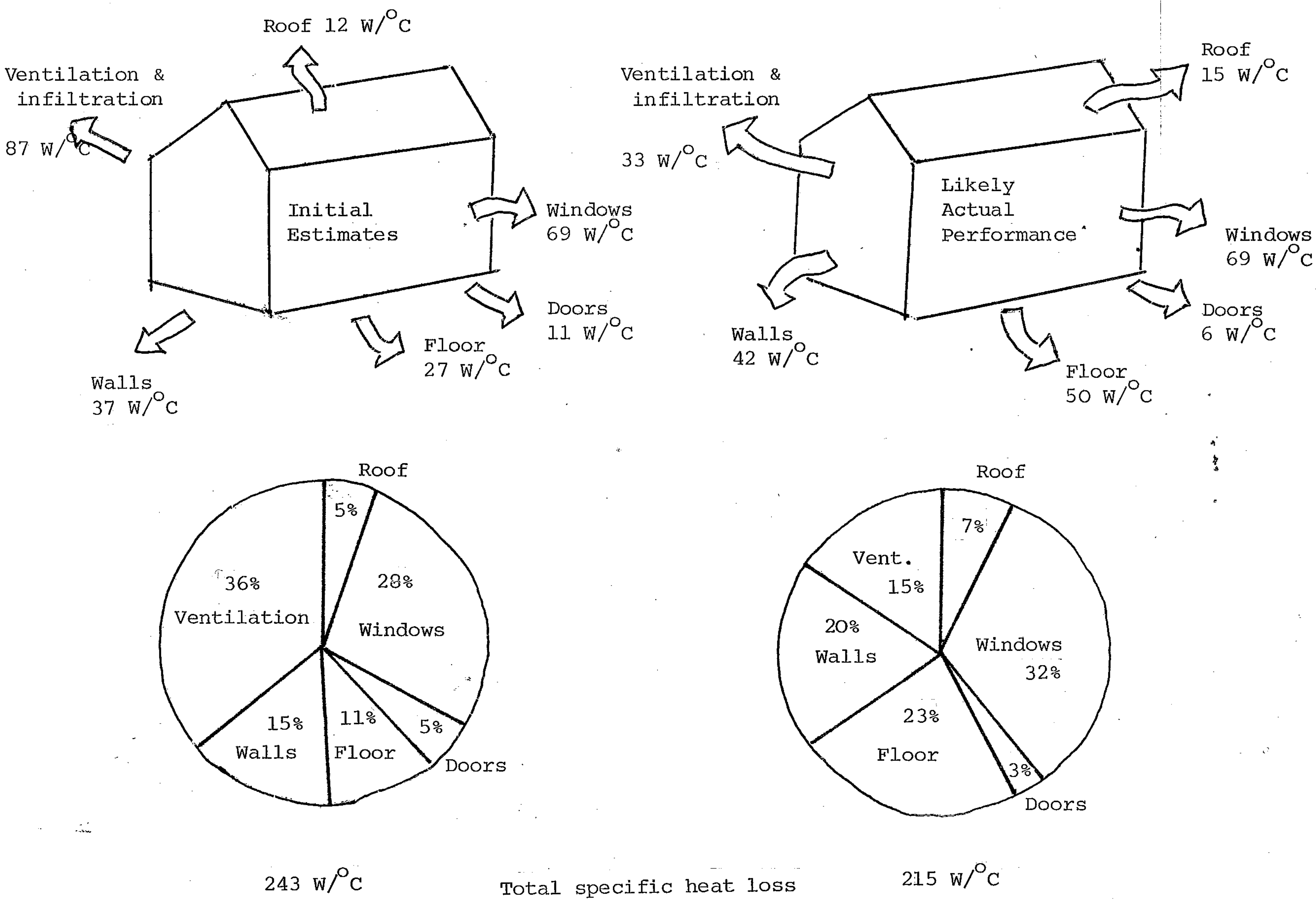
It should be borne in mind that the most accurately determined loss figure from the thermal calibration experiments is the house total heat loss figure of 215 W/°C. This is likely to be accurate to about ±10%. The subtotal of the losses of walls, windows, roof and doors can only be specified to about ±20%, since the floor and ventilation losses are only approximately known.

### 8.6.4. Fabric loss conclusions

Generally it would seem that with the exception of the floor the building fabric has performed thermally as well as can be expected. Indeed, if the floor had lived up to expectations, the overall building heat loss would have been about 20% better than the initial estimates, which is somewhat unusual in energy projects.

The performance of the floor cannot really be put down to poor insulation or poor design, given the lack of relevant information available at the design stage in 1977. This level of ignorance is discussed in the next section.

Figure 8.19 HOUSE HEAT LOSSES



## 8.7. Floor Loss Experiments

The results of the floor loss tests have been summarised in Section 8.5 but given the lack of published information on the subject it is worth describing the experiments in detail, together with the history of the current available theory.

### 8.7.1. Current theory and its history

Heat loss calculations for solid floors are normally based on the tables in the IHVE and CIBS Guides of floor loss as a function of plan geometry. The IHVE Guide, published in 1970, was all that was available at the Linford design stage, being updated to form the CIBS Guide in 1980. The tables of solid floor U-values were actually calculated by N.S. Billington using an analogue computer in the late 1940's and early 50's. Billington's book 'The Thermal Properties of Buildings' (Reference 8.4), published in 1954, makes it clear that there had been no systematic measurements of solid floor heat loss in the U.K. at that time and refers to some measurements in the U.S.A. Even these seem to be fairly limited in insulation level.

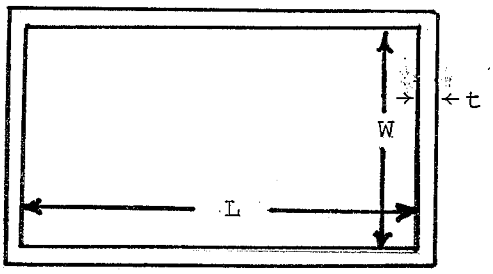
Since then, with the exception of the measurements by D. Spooner at the Cement and Concrete Association, which will be described later, there appear to be no actual detailed measurements of heat losses in solid floors in the U.K.

Billington's book refers to an earlier explicit mathematical solution for the heat loss of a solid floor. This equation, produced by H.H. Macey (Reference 8.5), has been incorporated into the CIBS Guide though the presentation is not likely to encourage its use.

Macey's equation relates the U-value of an uninsulated solid floor to the wall thickness and the building geometry (Figure 8.20):

$$U = \frac{4.K.B}{\pi.W} \operatorname{Tanh}^{-1} \left(\frac{W}{W + t}\right)$$

where K = Soil conductivity
W = Internal width of floor plan
t = Wall thickness
B = A shape factor depending on the length/breadth ratio:




| Ratio | L/W | B |
|---|---|---|
| 1.0 | (square) | 1.6 |
| 2.0 | | 1.3 |
| 3.0 | | 1.2 |
| 4.0 | | 1.15 |
| 5.0 | | 1.15 |
| 6.0 | | 1.1 |

Figure 8.20. U-Value (Macey's Equation) Depends on Building Geometry.

The function $\text{Tanh}^{-1} \left(\frac{W}{W + t}\right)$ (every architect's office has $\text{Tanh}^{-1}$ tables!) can be written in a much more manageable form:

$$\text{Tanh}^{-1} \left(\frac{W}{W + t}\right) = \tfrac{1}{2} \text{Log}_e \frac{1 + \left(\frac{W}{W + t}\right)}{1 - \left(\frac{W}{W + t}\right)} \simeq \tfrac{1}{2} \text{Log}_e \frac{2W}{t}$$

if $t \ll W$

This function is plotted in Figure 8.7.2 from which it can be seen that for many practical purposes it can simply be taken as equal to 2.

The importance of this equation is the statement that the floor U-value is proportional to the soil conductivity, a point that is not made at all in the IHVE Guide and certainly not stressed in the CIBS Guide.

The equation is in close agreement with Billington's computations, which were made using a soil conductivity of 1.4 W/m² °C.

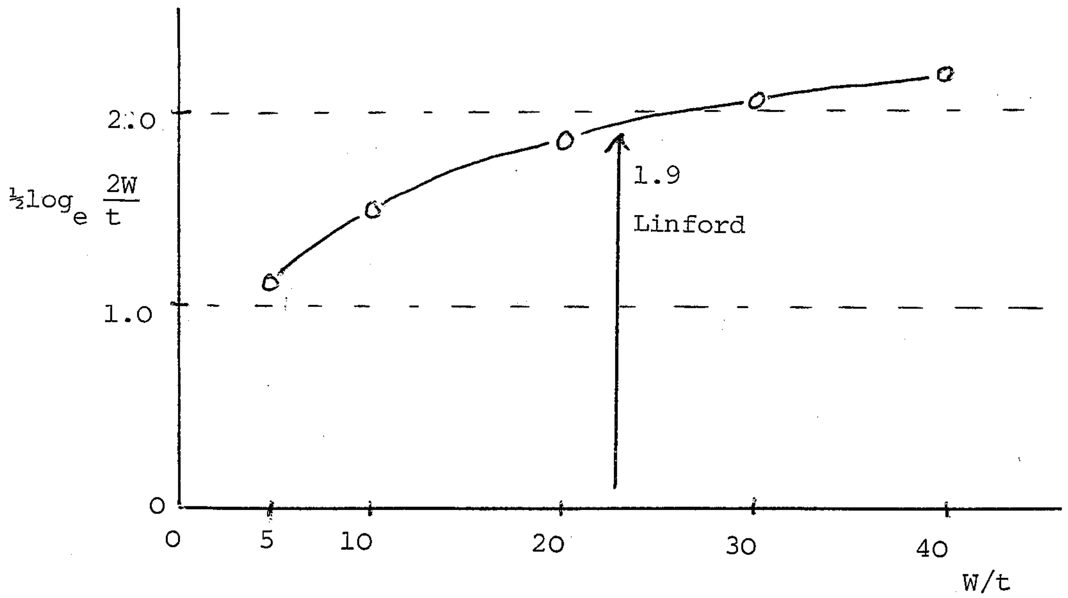



Figure 8.21 Effect of Wall Thickness on Floor Heat Loss

Soil conductivities depend not only on the soil type, but also on the water content, ranging from 0.25 W/m°C for dry chalk to 1.7 W/m/°C or more for very wet clay. To ignore these variations in soil conductivities make a mockery of the apparent precision of Billington's tables.

## 8.7.2. Heat flux sensors

The main measurements have been made with two heat flux sensors embedded in the surface of the floor at distances of about 0.6 m and 2 m respectively from the slab edge (see Figure 8.22). Both sensors were in the same corner of the house, just inside the living room windows (Figure 8.23). The lack of other sensors does create problems of whether the two spot values can be extrapolated to produce a total house floor loss.

The sensors themselves were made at the Open University and their fabrication and testing is described in Chapter 17. The overall accuracy including amplification errors is likely to be about ±15%.

## 8.7.3. Separation of solar effects

The siting of the flux sensors close to the window meant that the sun actually shone on the floor above them, indeed they have been used to estimate the solar energy stored in the floor from daytime into evening (see Chapter 10).

Separating out the solar effects from the steady heat loss is a little complicated. Figure 8.24 shows a plot of the heat flux through the floor edge sensor for October 1982 which clearly shows the magnitude of the solar generated heat fluxes. Even as large as they are, they represent only a small proportion of the solar energy incident on the floor surface.

It is not sufficient to merely average the daily heat fluxes, since on sunny days the floor surface temperature is well above the thermostatically controlled room temperature. On a shorter timescale the daily heat flow can be seen to take the form of a large surge of energy into the floor during the day, followed by a very long slow re-emergence back into the house (see Figure 8.25). This is likely to be very similar to the X-response function for the floor surface as calculated in response factor models (see Chapter 10).

Added to this dynamic response is a steady state heat loss dependent on the thermostatically controlled room temperature and some outside temperature. The closest that the varying heat flux is likely to get to its steady state value during the day is as dawn, just before a new surge of solar energy arrives. For this reason the floor loss has been calculated from 5 a.m. spot values rather than daily averages.

Even these dawn values require further correction. It has been assumed that there is a residual offset from the true steady state heat loss that is proportional to the solar radiation incident on the previous day. Correlation of dawn heat fluxes with the solar radiation of the previous day allowed the generation of a relation to correct for this residual error.

The two sensors have behaved very similarly as regards response to solar radiation, the one nearer the centre of the house being somewhat less responsive since the sun did not shine on it for quite so long each day.

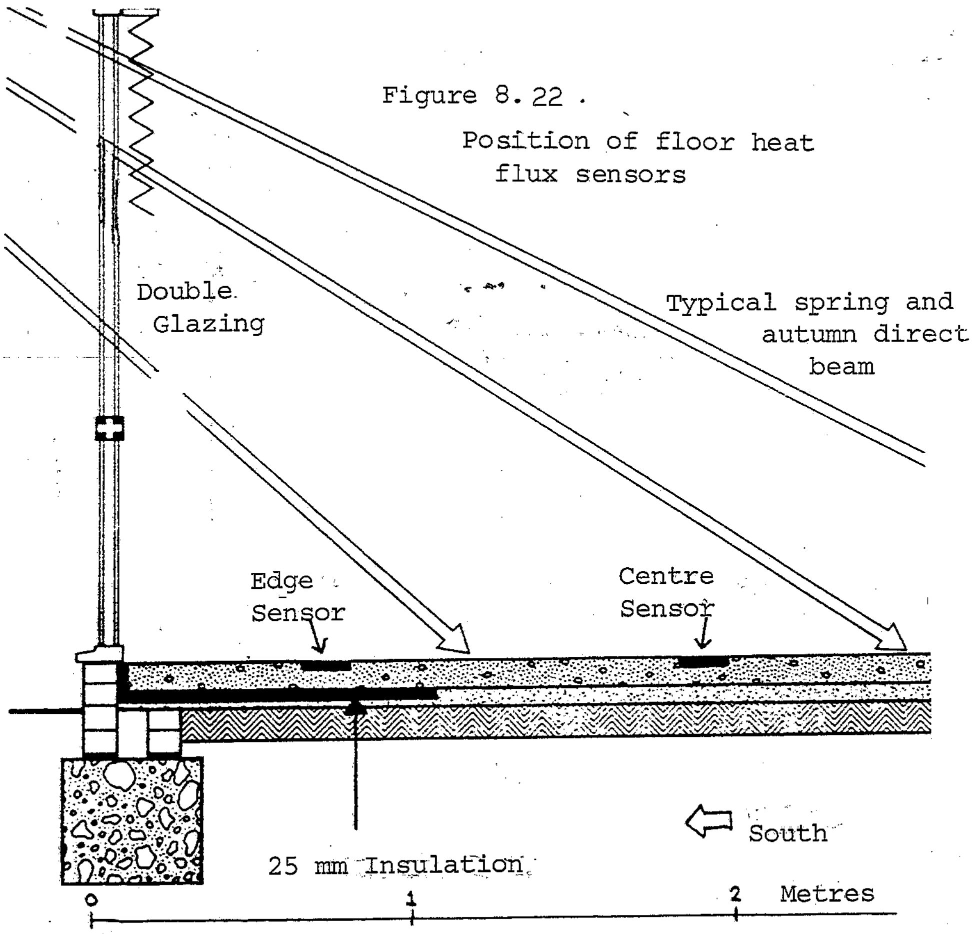



Figure 8. 22 . Position of floor heat flux sensors

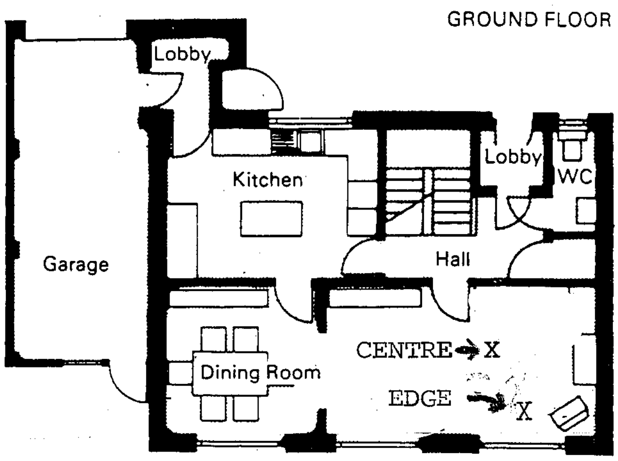



Figure 8. 23 Positions of floor heat flux sensors

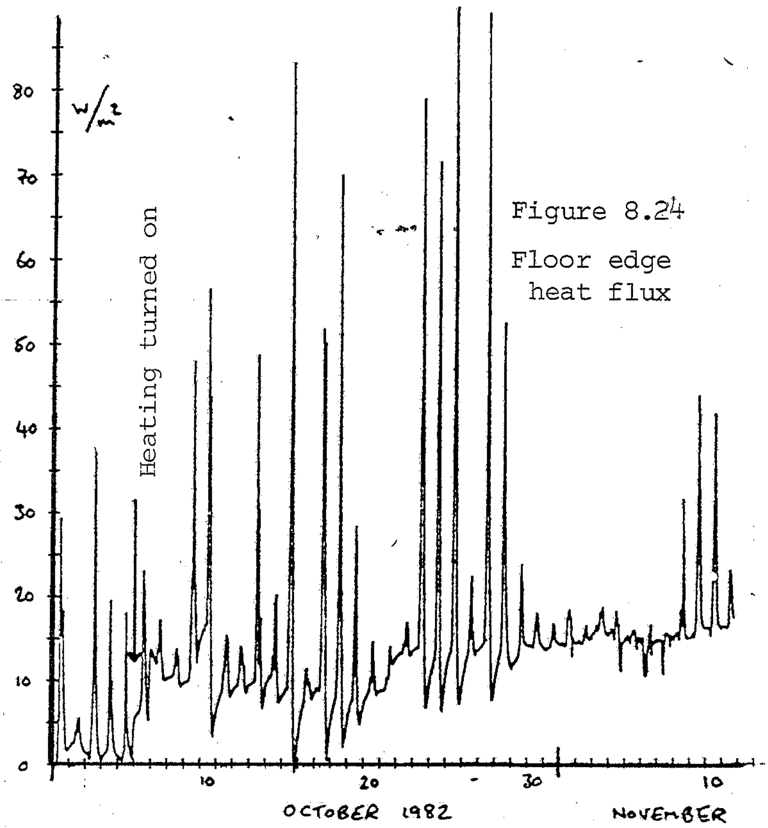



Figure 8.24

Floor edge heat flux

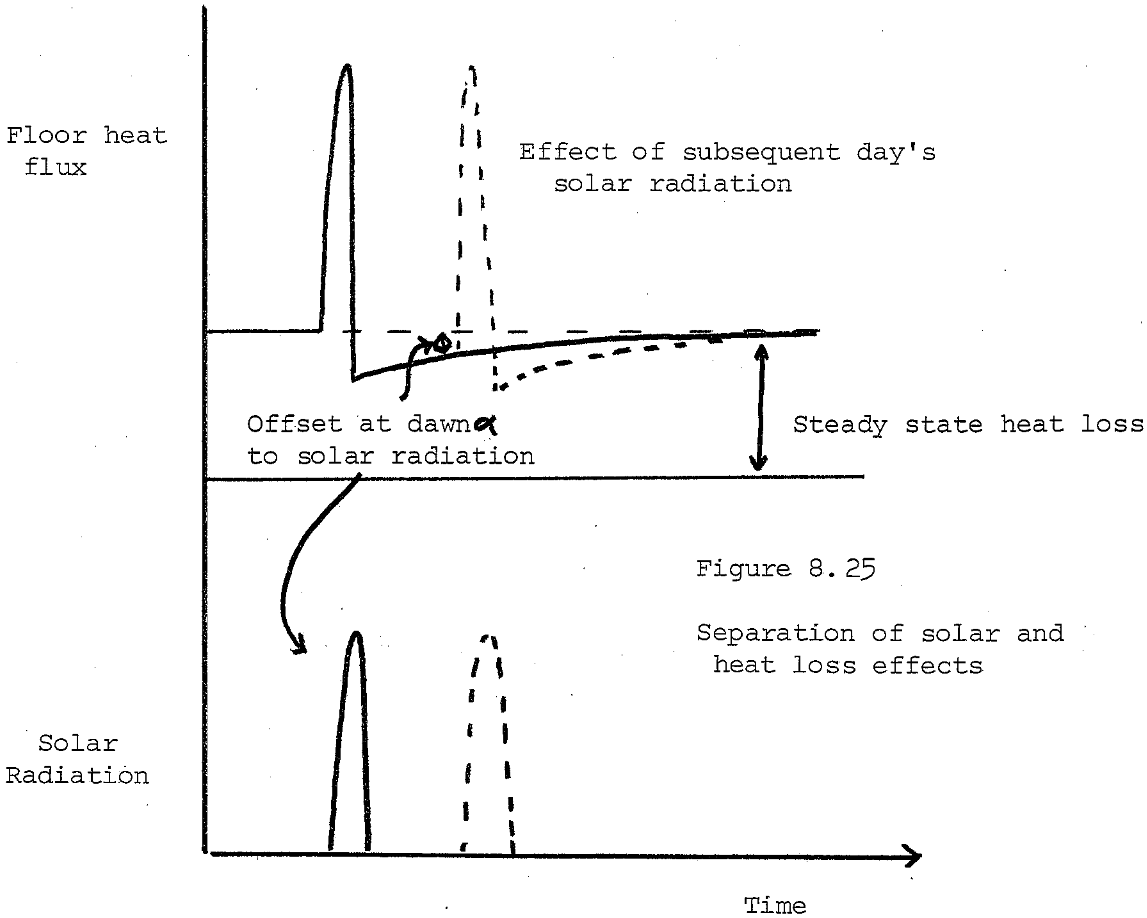



Figure 8.25

Separation of solar and heat loss effects

### 8.7.4. Variation of floor loss with time and insulation

Having separated out the short-term steady state floor heat losses from the solar effects, we can study the variation of heat loss over the year. Figure 8.26 shows the average of the responses of the two sensors as a function of time from the beginning on thermal calibration experiments in March 1982 to the end in June 1983. The summer points have been omitted since the correction for solar effects is only valid if the room temperature is held constant. Also plotted are the house internal and external temperatures and an assumed ground temperature. The house internal temperature over the period November 1981 to February 1982 was in the range 17-22°C though not under precise thermostat control.

The only thing that can really be said about the floor heat loss before insulation is that it rises in the autumn and falls in the spring and in a way not closely related to the external air temperature. After the extra insulation was added in December 1982 the floor heat loss is simply constant and bears no relation to external temperature at all. This result is so extraordinary that it sounds like gross equipment failure, however both sensors show the same thing and still continue to respond to very small solar effects penetrating the 50 mm insulation.

The measured heat losses have already been plotted against daily average $\Delta T$ in Figures 8.12 and 13 to give U-values according to the normal meaning of the concept, but the poor fit is clearly not very satisfactory and it is necessary to look into the dynamics of floor loss in more detail.

### 8.7.5. Cement and Concrete Association experiments

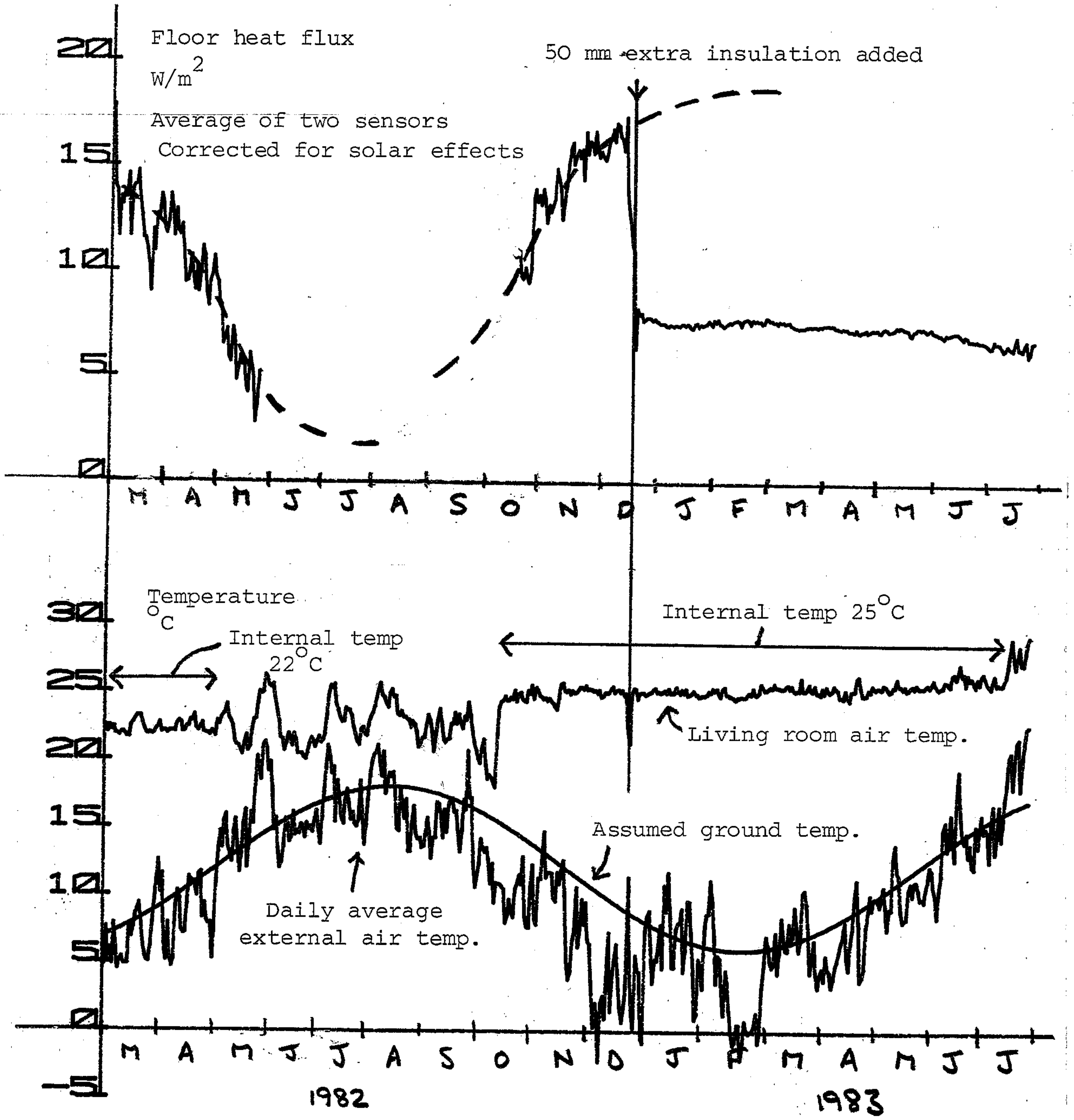
As a result of measurements on an unoccupied test house at the Cement and Concrete Association, D. Spooner has suggested that the heat loss of a solid floor is better expressed as a function of the difference between the house internal temperature and a ground temperature at a depth of about 1 metre (see Figure 8.27). This result can only strictly be taken as true of the tested structure, a solid concrete floor insulated over with 25 mm polystyrene, and in the particular experiments circumstances, i.e. thermostatically controlled intermittent heating (Reference 8.6).

Although this tidies up the response of the floor itself, it leaves us with an unknown quantity, the ground temperature under the house. Spooner's measurements show that this is related to the outside air temperature, but takes the form of an almost sinusoidally varying function lagging behind the swing in air temperature by about one month. (Figure 8.28.)

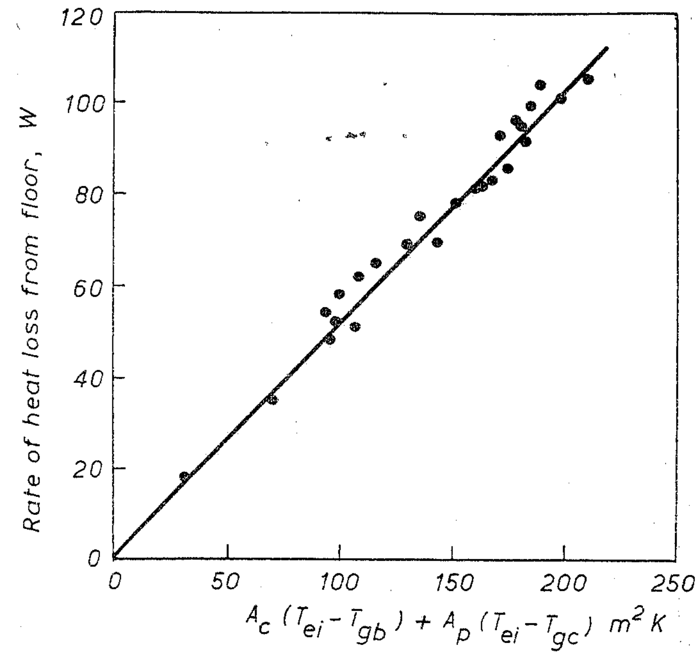
### 8.7.6. Linford results and ground temperature

Unfortunately at Linford no measurements of ground temperature were made and so we can only make an educated guess at the likely variation of ground temperature over the year. The function chosen has been a sinusoid fitted to a variety of published mains water temperature figures including some from the Bradville solar house (see Figure 8.29. This function has been used for energy calculations on active solar water heaters (Reference 8.8). It is also plotted in Figure 8.26 along with measured external air temperatures for the experimental period.

Figure 8. 26 Variation of floor heat flux over the year



Cement and Concrete Association Experiments




*Floor heat loss as a function of central and perimeter areas, and environmental and below-ground temperatures.*

Figure 8. 27 Floor heat loss as a function of internal temp and ground temp at a depth of 1 metre.

Ref. 8.7.

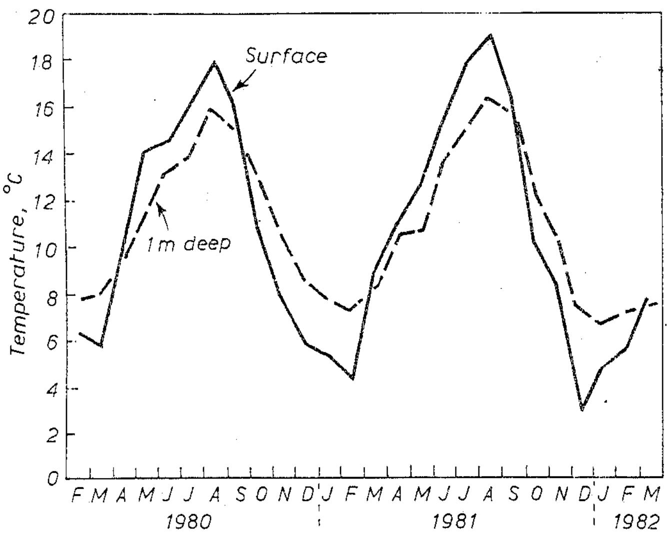



Figure 8. 28 Relationship of average ground surface temperature and temperature at depth 1 metre.

Ref. 8.7.

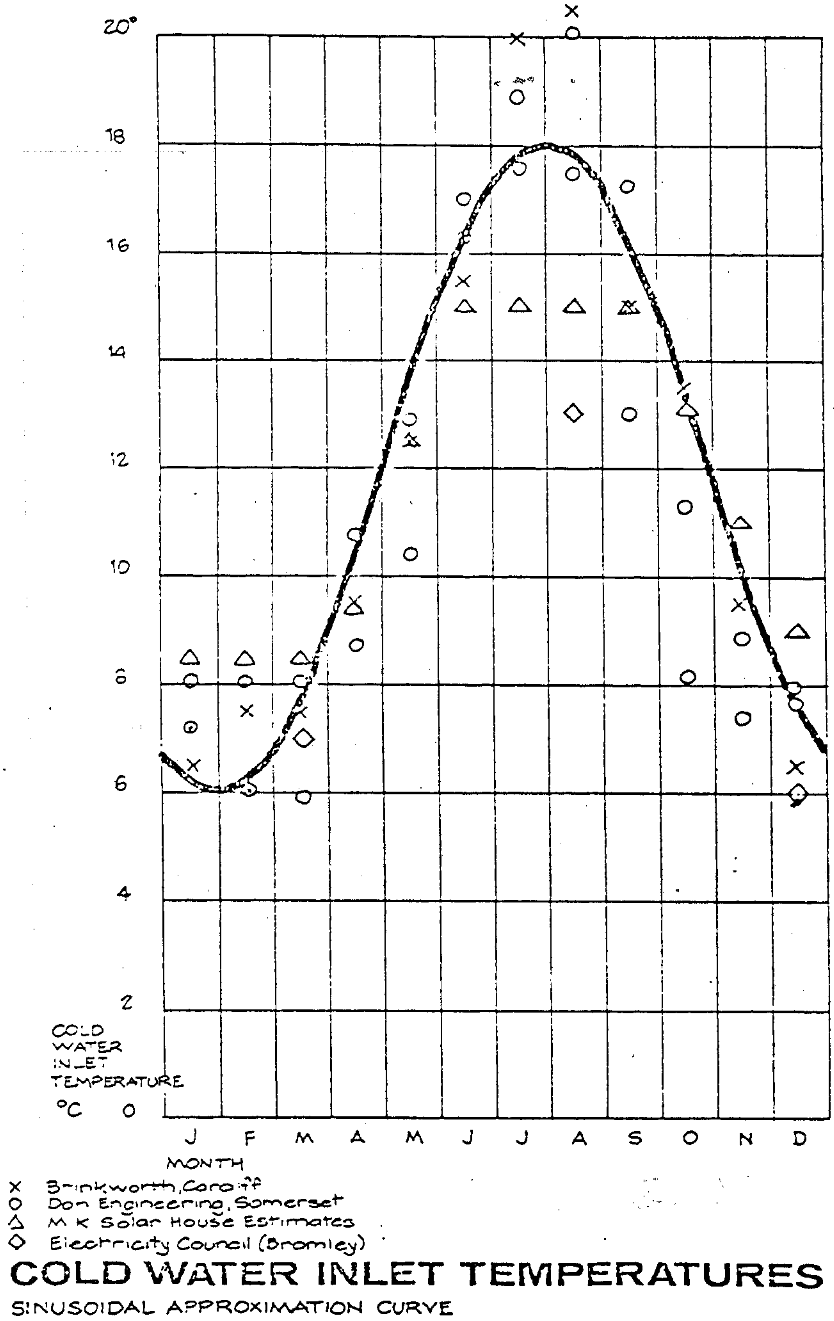



Figure 8. 29 Assumed ground temperature curve used for floor loss calculations

Ref. 8.8.

Plotting daily floor heat fluxes against $\Delta T$'s calculated using the measured internal house temperature and the assumed ground temperature (Figure 8.30) shows a much improved fit compared to Figure 8.12. Also the spring and autumn datasets are clearly separate. The difference between them may be real (the late summer of 1982 was very wet) or may simply be due to the wrong choice of ground temperature. The magnitude of the floor loss remains the same at about 0.9 W/m² °C.

Although this figure is well above the 0.5 W/m2°C predicted from Billington's tables, it could be compatible provided a soil conductivity of 2.6 W/m°C was assumed. Although the highest figure mentioned in the CIBS Guide is 2.0 W/m°C, the ground around the Linford houses is a particularly glutinous poorly drained clay and especially so in autumn 1982. There is also a possibility that actual water flow around and under the building might have increased the heat flow.

By way of contrast Spooner's results give a floor U-value slightly less than predicted from Billington's tables. The Cement and Concrete Association test house would appear to stand on fairly well-drained gravel soil which probably has a conductivity less than the 1.4 W/m°C assumed in Billington's calculations.

The assumed sinusoidal ground temperature curve has been used to calculate the floor heat loss in the occupied houses, using an U-value of 0.9 W/m² °C, to allow estimates of their fabric heat losses and solar apertures.

This ground temperature curve still does not explain the bahaviour of the floor after the installation of the extra insulation, with a near constant heat loss. For this to be related to ground temperature would require an almost constant function, not a large sinusoidal swing.

It would appear that ground temperature is very strongly a function of depth. Figure 8.31 shows average measured ground temperatures at depths down to 20 metres. Although at one metre depth ground temperatures have a large annual swing, at a depth of 3 metres the swing is reduced to less than 4°C and is more than four months out of phase with the air temperature.

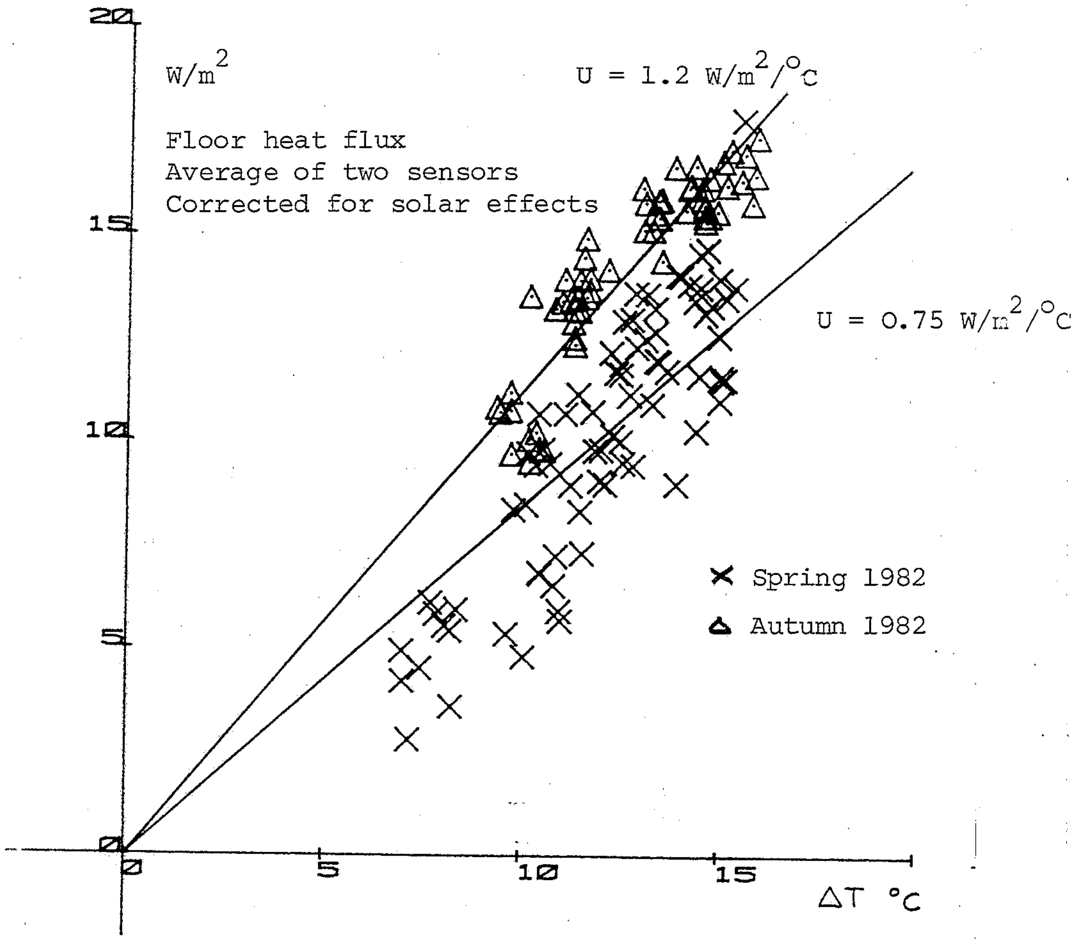
The measured heat loss is thus plausible if it is referred to a deep soil temperature, though why the relation should change with insulation level seems a mystery. Assuming a soil temperature of 10°C, the measurements give a floor U-value of about 0.5 W/m² °C corresponding very well with the U-value of 50 mm polystyrene as if it had been placed in a wall.

### 8.7.7. Floor insulation and thermal calibration

It is possible to check the reduction in house heat loss as a result of insulating the floor by using thermal calibrations before and after the event. These show a marked change in apparent house heat loss but the results are not compatible with the measured change in floor heat flux from the two sensors. There are three alternatives to resolving the incompatibility:

(a) The building fabric heat loss changed in December 1982.

(b) The estimation of the total floor heat loss from the two sensors is wrong before insulation.




Daily average ΔT calculated from living room temp. and assumed ground temp.

Figure 8. 30 Relationship of floor heat flux to assumed ground temperature

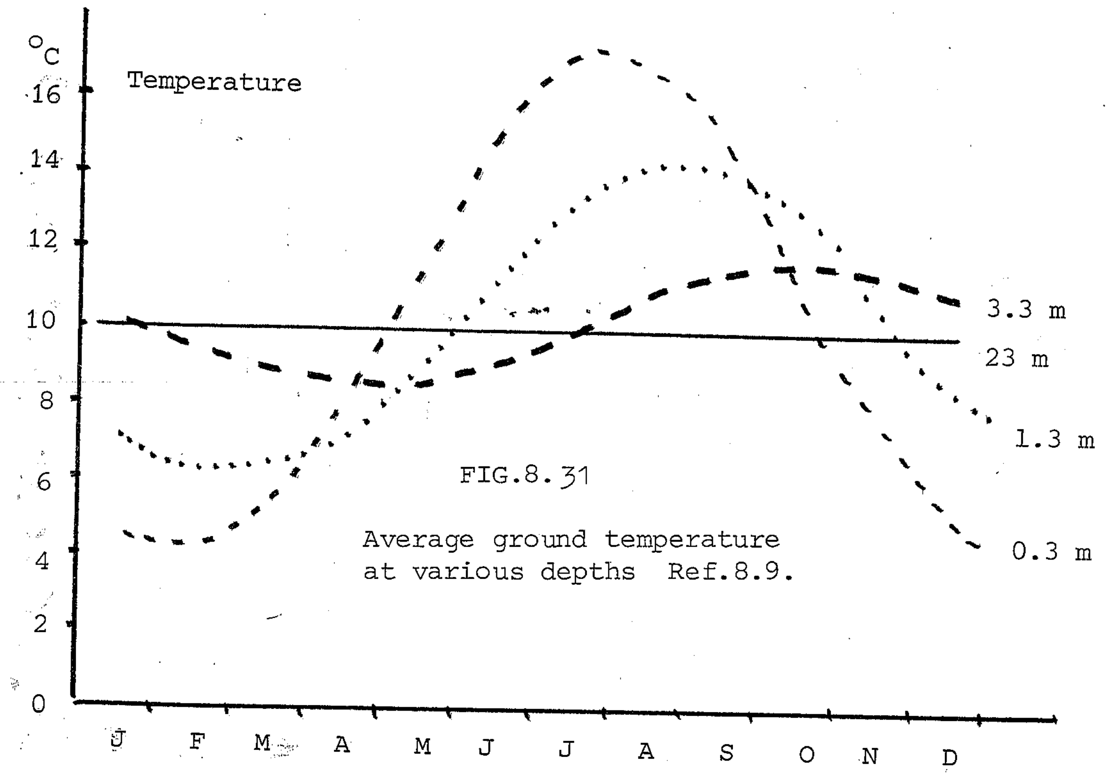



FIG.8.31

Average ground temperature at various depths Ref.8.9.

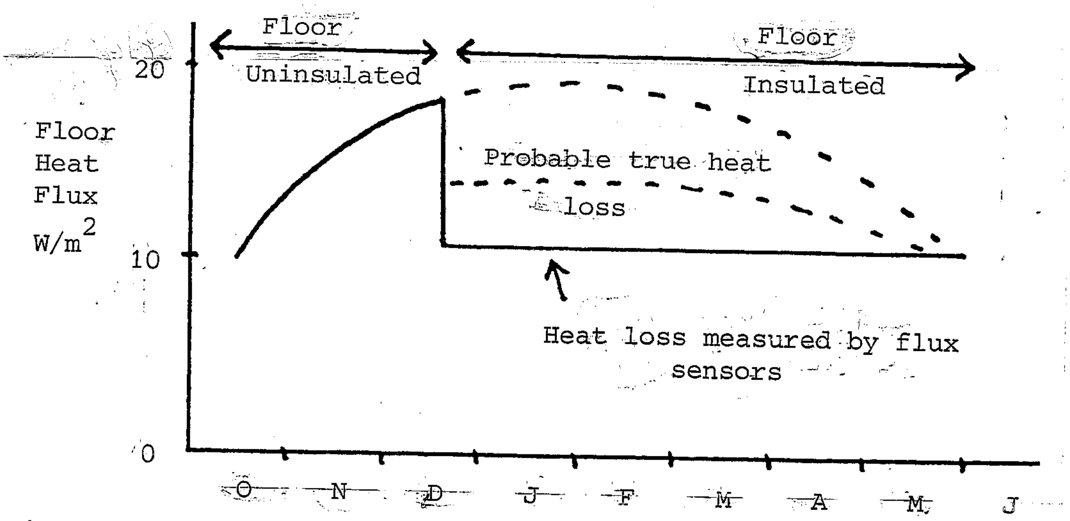



Fig. 8.32 Floor heat loss after insulation as deduced from thermal calibrations.

(c) The estimation of the floor heat loss after insulation is wrong.

Of the three alternatives the last seems the most likely, since the sensors themselves are under 50 mm insulation and yet there are large cold bridges in the insulated floor in the shape of the dense concrete partition walls.

The floor heat flux sensors predict a change in floor loss of 8 kWh/day in house heat loss but the thermal calibrations give an estimate (admittedly not very statistically hard) of 3.8 kWh/day. It is thus likely that the true pattern of total floor heat loss is as in Figure 8.32 rather than in Figure 8.26 but given the lack of measurements this is mostly guesswork.

For the purposes of calculating solar apertures in Chapter 10, the floor loss after insulation has been taken from the actual heat flux sensor measurements. The discrepancy shows up as higher estimates of fabric heat loss than the 130 W/°C quoted in this section. The effects of these kinds of uncertainty on the determination of solar aperture and the consistency of successive thermal calibrations will be discussed in the separate thermal calibration report.

## 8.7.8. Conclusions on floor heat loss

1. The floor U-value before insulation is approximately 0.9 $W/m^2$ °C, considerably larger than the figure of 0.5 $W/m^2$ °C predicted. The most likely cause is a high soil conductivity possible with ground water flow.

2. The U-value is best expressed referred to an immediate subsurface ground temperature rather than air temperature.

3. The addition of 50 mm of extra insulation over the floor has reduced the heat loss by approximately 25%, though a higher figure would be possible if the insulation had extended under the partition walls.

4. The heat loss of this floor structure would appear to be best expressed in relation to a near constant deep ground temperature of about 10-12°C.

5. It has become clear that the actual understanding of the mechanisms of solid floor heat loss is extremely poor. The body of knowledge in the U.K. rests almost entirely on calculations made 30 or more years ago. These calculations did not include the dynamic properties of floor loss. There appears to have been no systematic programme of measurement of solid floor heat loss in the U.K.

6. Although the calculation methods available make it clear that soil conductivity is an important factor in solid floor heat loss, this is not made clear in the data available to architects in the IHVE and CIBS Guides.

7. It would seem desirable that there is a proper programme of investigation of solid floor heat loss, especially at insulation levels compatible with the current building regulations.

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# 9. INFILTRATION & VENTILATION

CONTENTS



This chapter deals with the air infiltration and ventilation characteristics of the houses. Results from extensive infiltration measurements in the test house are given. These were used to develop a theoretical model for describing the infiltration characteristics of the test house. This model was used to investigate the effect of site layout, and to estimate infiltration rates and heat losses in the occupied houses.

# 9.0 INFILTRATION AND VENTILATION

## 9.1 Introduction

Air infiltration and ventilation in well insulated houses can constitute a much larger proportion of the total heat loss than in poorly insulated ones.

The effects of insulation, its incorporation into the design and its practical application are now fairly well understood. Infiltration on the other hand is very poorly understood from a theoretical, design or practical point of view.

The study of infiltration was therefore considered to be an important issue in this project. It was felt important to come up with a firm estimate of the energy consumption attributable to infiltration and ventilation. To this end the following measurements were made:

i) pressurisation tests on the test house and four occupied houses to establish leakage rates.

ii) infiltration and ventilation measurements - by British Gas and the Open University in the test house.

iii) window openings in four occupied houses.

It was hoped that the detailed monitoring in the test house would generate a theoretical relationship between infiltration rate, wind speed and direction, and temperature difference, so that estimates of the infiltration rates could be made for the other, occupied houses in the project. Also it was hoped that the window opening data would give an indication of ventilation rates.

## 9.2 Terminology - leakage, infiltration, ventilation

The study of air movement in houses involves three slightly different concepts - leakage, infiltration and ventilation (Figure 9.1).

Leakage is a term which describes how tightly a house is sealed. This is usually determined by measuring the air flow through the house when it is pressurised.

Infiltration is air moving through the house under different conditions of wind speed, direction and temperature with windows closed. This is influenced by the size of cracks around doors and windows and in the structure itself. It is also dependent on the relative position of these cracks. Infiltration is usually measured using tracer gases such as nitrous oxide.

Ventilation is the movement of air through a house under real conditions with windows or other openings (extractor fans, etc.) being used by the occupants. While infiltration is fortuitous, ventilation is intentional. It can also be measured by tracer gas techniques.

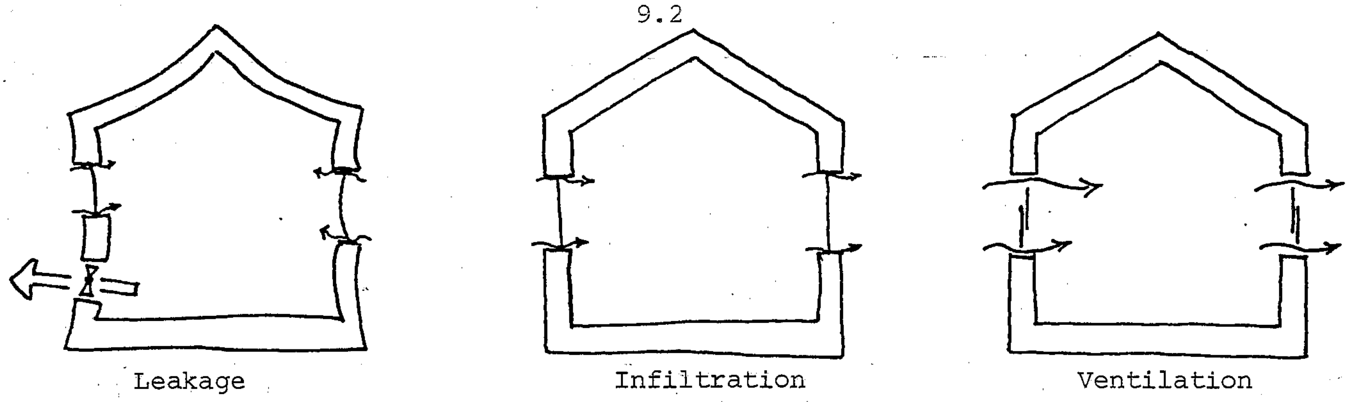



Figure 9.1 The three concepts involved with air movement in houses

Measurements of leakage and infiltration allow the development of theoretical prediction techniques to describe infiltration under varying external conditions. However the number of combinations of window and door openings and their random occurrence makes it difficult to theoretically predict ventilation rates.

## 9.3 Leakage

Pressurisation tests were carried out on four occupied houses and the test house. These measurements proved to be extremely useful because they a) gave a comparison of the air tightness of the different houses, b) showed the effect of applying draughtstripping, c) showed how leakage changed over a nine month period and d) gave a comparison between other houses measured in a similar way in the U.K., Scandinavia and Canada.

### 9.3.1 The measurements

The tests were carried out by British Gas and the Open University over two periods in March 1981 and November-December 1981. The method involved substituting a window with a purpose-built fan assembly (see fig. 9.2).

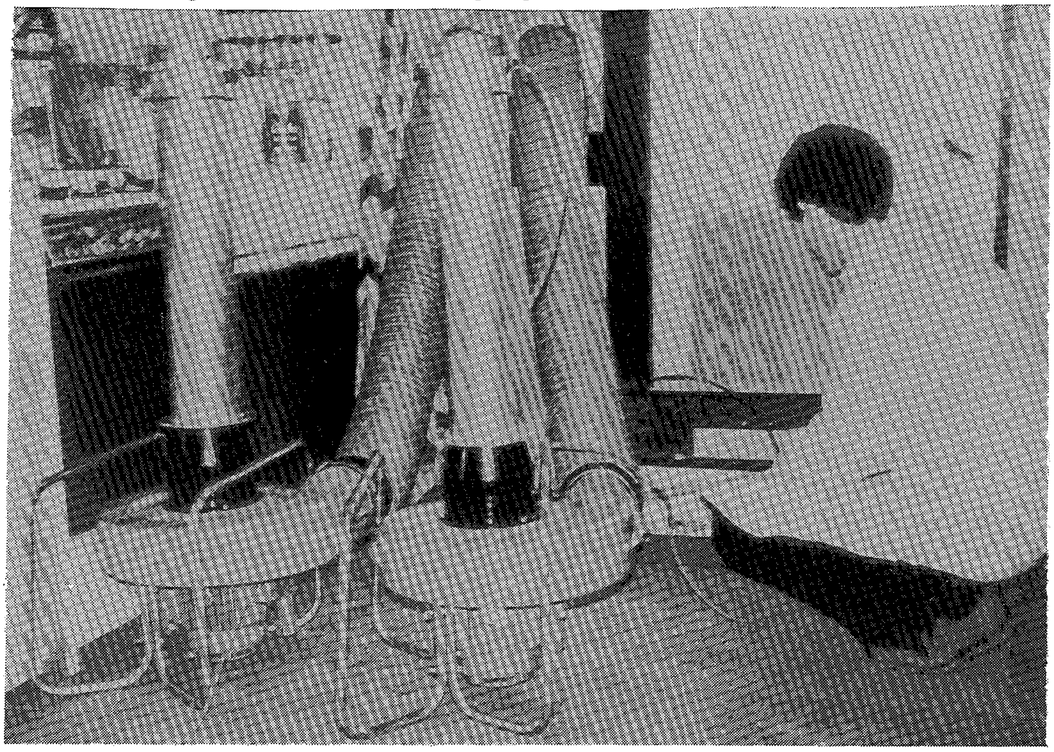


Figure 9.2 The pressure test rig

The fan was used to pressurise the house and the resulting airflow calculated by measuring the pressure difference across a calibrated nozzle in the fan output.

The house is pressurised at various air flow rates and the pressure difference, P, between the inside and outside of the house measured using a sensitive manometer (basically a sloping glass tube filled with water). The air flow rates can be plotted against pressure, as in figure 9.3, either in $m^3/s$ or, by dividing by the house volume, as ac/h. This plot can then be used to estimate the flow rate at some standard pressure, such as 50 Pascals, for comparitive purposes.

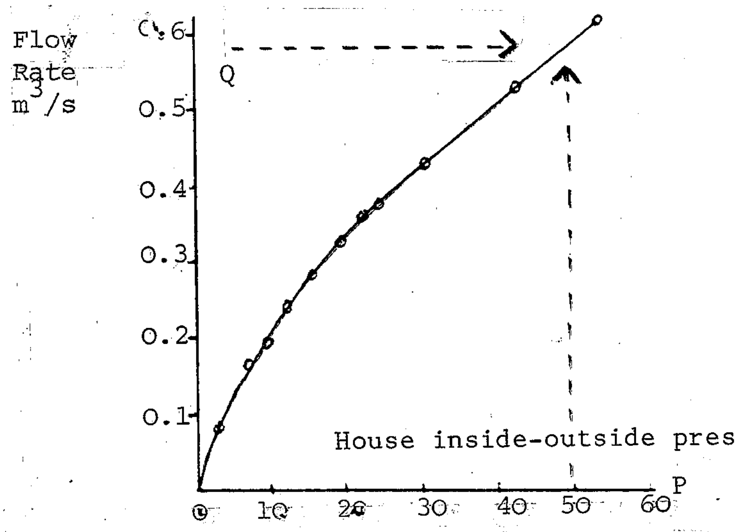



Figure 9.3

A sample house test leakage curve

The test is normally applied to a house as a whole, for which all the internal doors must be kept open. The method can also be used to determine the leakiness of individual rooms within a house. This is done using a second fan fitted to a substitute external door or window within the room. The connecting door between the room and the rest of the house is sealed with masking tape, so that air can only flow into the room from outside, through local cracks in the fabric adjacent to that room. The flow rates of both fans are then balanced, to achieve a uniform pressure throughout the house. The air flow through the second fan is then the component for the individual room only.

It should be remembered that this standard test is carried out at abnormally high pressure differences - 50Pa is roughly equivalent to a hurricane force gale - and the results from pressure tests do not necessarily say much about the actual infiltration rates with normal external conditions, although ways of relating the two are discussed in appendix 9.2. At least, the method is very useful for comparing different houses with each other and with "normal" values for U.K. houses.

### 9.3.2 Results of leakage tests

The results of the leakage tests are listed in Table 9.1. The following points should be noted:

i) "Full draught stripping" means draught stripping applied to the front and rear kitchen door (to the garage), and to the french windows in the lounge. The sliding-pane double glazing has a form of draught stripping already built into the design.

ii) The houses have three small sliding vents above the windows in the kitchen, downstairs W.C. and the shower/toilet off the main bedroom. The "normal" condition is taken as closed.

iii) For the loft hatch, the "normal" condition is taken as unsealed.

iv) The houses were not draught stripped at the time of the March 81 tests. It was decided to fit draught stripping to each house prior to the first space heating season (1981/82), due to the obviously poor fitting front door and french windows. This was done during September 1981.

Further details of these measurements will be found in reference 9.5.

### 9.3.3 Discussion of results

From Table 9.1 the following comparisons can be made:

(i) General airtightness

Several tests are directly comparable, as they were carried out within two weeks of each other, with each house fitted with draught stripping and with vents closed (Table 9.2).

Table 9.2 Leakage rates in five houses all draught stripped and with vents closed

| Test | House | Air flow at 50Pa | Air changes/hr at 50Pa |
|---|---|---|---|
| 2 | 35 | 0.444 | 6.4 |
| 4 | 36 | 0.594 | 8.6 |
| 8 | 37 | 0.620 | 8.9 |
| 11 | 38 | 0.570 | 8.2 |
| 12 | 39 | 0.510 | 7.3 |
| | Average | 0.548 | 7.9 |

Table 9.1 Results from leakage tests carried out under various conditions

| Test No | House | Date | Conditions | | | Air flow at 50Pa $Q_{50}$ | Air change rate at 50Pa $A_{50}$ | Effective orifice area at 50Pa |
|---|---|---|---|---|---|---|---|---|
| | | | Draught Stripping | Vents | Left Hatch | | | |
| | | | | | | $m^3$ sec | ac/h$^{-1}$ | $m^2$ |
| 1 | 35 | 6/3/81 | None | Closed | Unsealed | 0.560 | 8.1 | 0.100 |
| 2 | " | 2/12/81 | Full | Closed | Unsealed | 0.444 | 6.4 | 0.078 |
| 3 | 36 | 6/3/81 | None | Closed | Unsealed | 0.680 | 9.8 | 0.120 |
| 4 | " | 3/12/81 | Full | Closed | Unsealed | 0.594 | 8.6 | 0.104 |
| 5 | 37 (test house) | 6/3/81 | None | Closed | Unsealed | 0.685 | 9.9 | 0.120 |
| 6 | " | " | None | Open | Unsealed | 0.695 | 10.0 | 0.130 |
| 7 | " | " | Full | Closed | Unsealed | 0.455 | 6.6 | 0.080 |
| 8 | " | 18/11/81 | Full | Closed | Unsealed | 0.620 | 8.9 | 0.109 |
| 9 | " | " | Full | Closed | Sealed | 0.600 | 8.6 | 0.105 |
| 10 | 38 | 6/3/81 | Full | Closed | Unsealed | 0.560 | 8.1 | 0.100 |
| 11 | " | 30/11/81 | Full | Closed | Unsealed | 0.570 | 8.2 | 0.098 |
| 12 | 39 | 30/11/81 | Full | Closed | Unsealed | 0.510 | 7.3 | 0.089 |

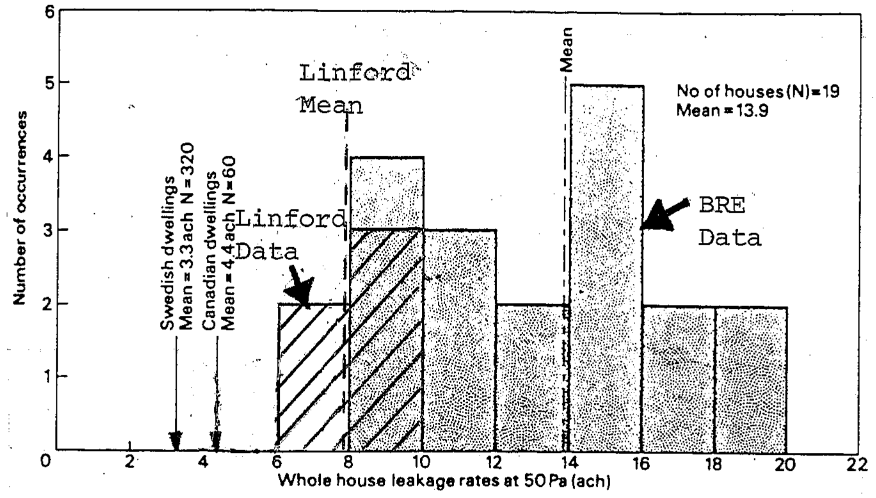



Figure 9.4 The results show that the Linford leakage rates are well below those measured by BRE

These results can be compared with a survey of 19 U.K. houses carried out by BRE (Figure 9.4). These houses were built within the last 20 years, and cover a range of construction types (reference 9.1). Clearly the Linford houses are at the bottom of the range, while not being as airtight as typical Swedish and Canadian houses which are generally built to a higher standard of airtightness. The mean of the Linford results is 7.9 ac/hr, compared with 13.9 for the BRE sample. It is not claimed that the six Linford results constitute anything like a statistically significant sample, but it seems that they are considerably more airtight than typical U.K. dwellings.

The Linford measurements from Table 9.2 can also be compared with measurements in four Pennylands and three Neath Hill houses carried out in July 1983, again by British Gas.

The Neath Hill houses are more typical of the U.K. building stock. They are "normal" houses built to pre 1982 building regulations but insulated with UF foam cavity fill. Their performance is being compared with some other low energy houses at Pennyland.

Table 9.3 Comparison of pressure tests at Linford, Pennyland and Neath Hill

| Linford ac/h at 50Pa | Pennylands ac/h at 50Pa | Neath Hill ac/h at 50Pa |
|---|---|---|
| 6.4<br>8.6<br>8.9<br>8.2<br>7.3 | 5.4<br>6.0<br>5.3<br>5.0 | 12.2<br>14.2<br>16.2 |
| Average 7.9 | Average 5.4 | Average 14.2 |

The Neath Hill houses lie close to the average for the BRE sample, while the Pennyland houses are even tighter than Linford, being only 23% more leaky than the Canadian mean shown in Figure 9.4.

The difference between Pennylands and Linford may be due to their smaller size, smaller window area, the fact that they are terraced rather than detached, and perhaps the fact that they have an inner skin of in situ concrete, rather than block construction.

(ii) Effect of draught stripping

The effect of draught stripping on house 37 can be seen by comparing tests 5 and 7. The air change rate drops from 9.9 ac/h to 6.6 ac/h - a reduction of 33%. This suggests that approximately 1/3 of the total leakage area of the house consists of gaps around the front and rear doors, and the french windows, while the remaining 2/3 consists of "background" leakage through the various cracks and crevices in the general building envelope. This can be viewed from two directions - as an indication of tightness of the basic building envelope, or the original poor fit of the front and rear doors and french windows. Both statements are probably justified.

(iii) Effect of vents

The effect of the sliding vents in the kitchen, W.C. and shower room can be seen by comparing tests 5 and 6, carried out in the test house. The air change rate is increased from 9.9 to 10.0 on opening the vents. This is only a 1% change in the whole house leakage, which is small enough to be ignored as a parameter in estimating ventilation rates in the occupied houses. The presence of the vents in these rooms however, may well be offering a degree of localised control over ventilation rates to help avoid the build up of smells and humidity. At the very least, their use by the occupants may have avoided windows being opened and possibly left open for longer than is necessary.

(iv) Effect of loft hatch

The loft hatch was sealed with masking tape. Leakage through the loft hatch appears to be about 3% of the total, which is small, as can be seen from tests 8 and 9.

(v) Increase over time

It is expected that the crack area in houses will increase over a period of time due to settling and drying out of the structure, causing cracks to widen. This is most likely during the first 12 months following construction. The test house was completed about January 1981. Test 7 was carried out in March 1981, and test 8 in November 1981, which allows a period of 8 months for any such settling and drying out to occur. The air change rate over this period increased from 6.6 ac/h to 8.9 ac/h (at 50Pa), an increase of 35%. However, comparison of tests 10 and 11 show that there was virtually no change over the same period, for house 38.

These results are inconclusive and should be seen in the light of leakage tests done on timber frame houses at Abertrydwr (Ref. 9.2). Although these houses have a somewhat different construction, tests done a year after completion showed a doubling of air leakage at 50 Pa pressure.

(vi) Individual room leakage

As part of the leakage tests carried out by British Gas during November 1981, the leakage characteristics of individual rooms were measured in the test house (no. 37), using the method described earlier. The results are shown below:

Table 9.4 Room pressure tests

| | Flow at 50Pa $m^3/s$ | % | Room volume $m^3$ | Air changes at 50Pa ac/h |
|---|---|---|---|---|
| N bathroom | 0.064 | 19 | 10.0 | 23.0 |
| S bedroom (without shower room) | 0.048 | 14 | 29.3 | 5.9 |
| N kitchen | 0.044 | 13 | 32.5 | 4.9 |
| S lounge/dining room | 0.043 | 12 | 66.9 | 2.3 |
| N shower room (off bed. 1) | 0.042 | 12 | 8.0 | 18.9 |
| S bedroom 2 | 0.039 | 11 | 25.8 | 5.4 |
| S bedroom 4 | 0.026 | 8 | 17.2 | 5.4 |
| N bedroom 3 | 0.016 | 5 | 17.8 | 3.2 |
| N front door lobby | 0.012 | 3 | 3.9 | 11.1 |
| N toilet | 0.010 | 3 | 6.1 | 5.9 |
| TOTAL | 0.344 | 100 | 217.5 | WHOLE HOUSE AVERAGE 5.7 |

The whole house measurement was 0.62 $m^3/s$ (loft hatch unsealed). The difference between the sum of the individual room leakages and that for the whole house is partly due to the contribution from the hall and stairwell, which cannot be measured practically, and partly due to experimental error. It is difficult to prevent these errors in an experiment of this kind. There will inevitably be leakage between rooms during the test.

It is interesting to note that the air change rates through the bathroom and shower room are very high. This could be the result of leakage into the casing around the soil and vent pipe. If these figures were reduced to a more average figure of, say, around 5 ac/h in these rooms, then the total whole house leakage would be reduced by about 1 ac/h.

The fact that air change rate in the living/dining room is only 2.3 ac/h (at 50Pa) suggests that the large windows are not detrimental in terms of leakage.

Figure 9.5 shows the breakdown between upstairs and downstairs and north and south facing rooms. Twice as much air is leaking from upstairs rooms as downstairs. This is possibly due to the high leakage from the upstairs bath and shower rooms.

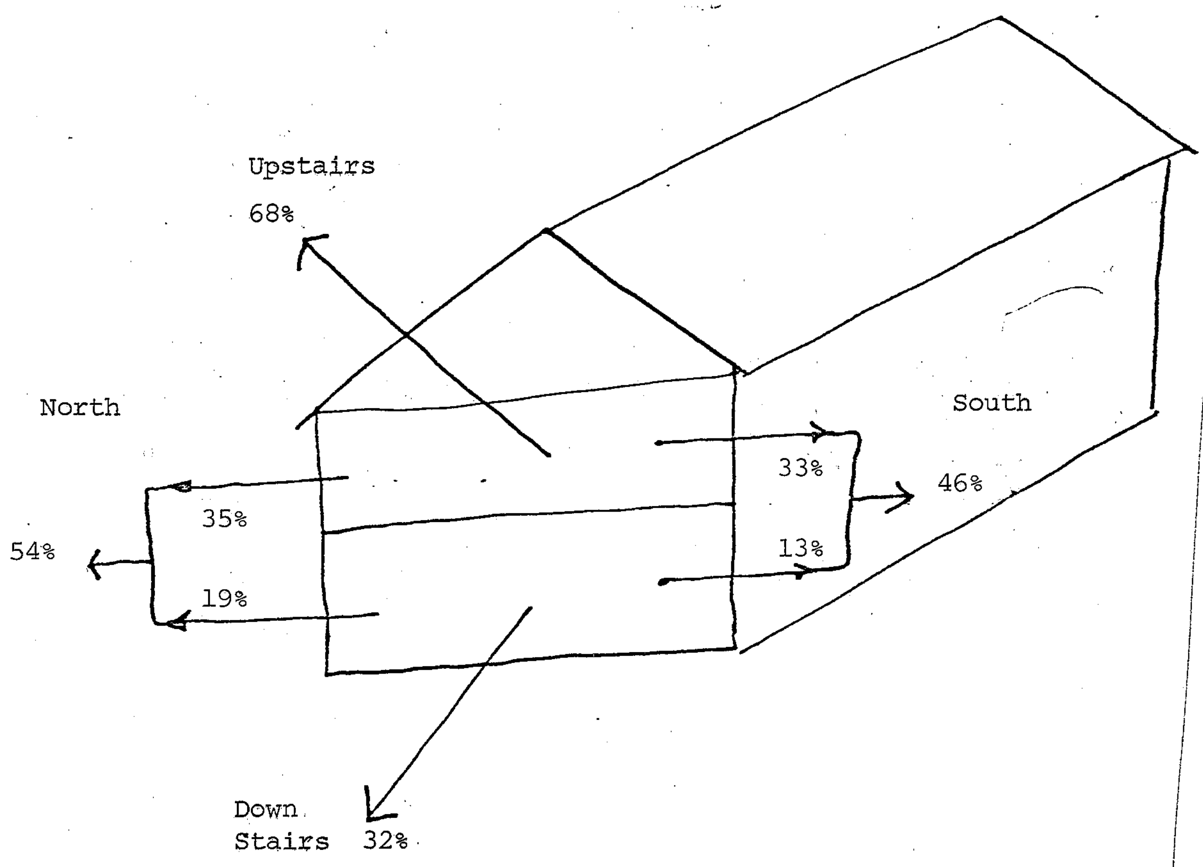



Figure 9.5 The breakdown of leakage between north and south, and upstairs and downstairs

## 9.4 Infiltration

### 9.4.1 Brief theory

During cold windless periods infiltration will be caused by the tendency for warm air in the house to rise, leaking out of cracks upstairs while being replaced by cold outside air through cracks downstairs. When wind speeds rise above about 2 m/s, wind forces become dominant. These set up areas of pressure and suction on the building fabric which cause air to leak into and out of the house.

Infiltration of outside air through cracks in the building structure is therefore governed by these two distinct effects: a) the stack or buoyancy dominated region and b) the wind dominated region.

Between these two regions there is a transition zone as shown in figure 9.6.

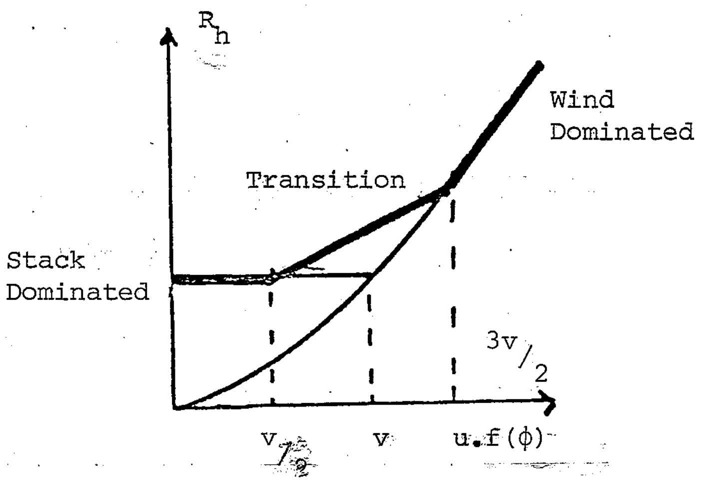



Figure 9.6 At low wind speeds air infiltration is dominated by the stack effect, at higher speeds the air change rate increases with wind speed

Infiltration is also dependent on wind direction in relation not only to the positions of the cracks but also to the position of other buildings or planting around the house which will shelter it from winds in certain directions.

Any theoretical simulation of infiltration would be extremely difficult because of all these interactive variables. Therefore extensive monitoring was carried out in the test house to attempt to measure the infiltration rate accurately.

### 9.4.2 Measurements

Measurements of infiltration rates in the test house were made as follows:

i) November and December 1981: British Gas tests using their 'autovent' microprocessor-controlled system. This maintains a constant level of nitrous oxide tracer gas in all zones of the house.

ii) February - April 1982: Open University tests using a simple rig which measured the rate of decay of a fixed injection of nitrous oxide gas. It was adapted for continuous automatic operation (see Chapter 16).

iii) November 1982 - March 1983: Second phase of Open University monitoring.

The OU measurements were extensive in number - over 570 measurements - and covered a wide range of weather conditions.

The British Gas measurements were more accurate, but only covered a short period of time. However, a sufficient variety of weather conditions were encountered to enable an empirical prediction formula to be fitted to the data (carried out by British Gas). The derivation of this formula is given in full in appendix 9.1. It proved most useful in the analysis, for:

i) estimating infiltration rates in the test house when no measurements were made - this enabled more extensive use of monitored data for general thermal calibration (see chapters 8 and 10). The formula could reliably predict infiltration rates to within $\pm$ 0.2 ac/h.

ii) making crude estimates of the infiltration and ventilation rates in the occupied houses.

iii) examining the energy implications of siting and orientation.

Details of the British Gas measurements will be found in reference 9.4.

### 9.4.3 Results

(i) OU measurements

Figure 9.7 shows measurements in the test house over 2 months in March and April 1982. Each consecutive measurement was generally separated by 3-4 hours.

Internal doors were open, windows were kept closed, and the internal air temperature was kept at a constant and uniform 22$^{\circ}$C, as part of the heating experiments to determine fabric heat losses and solar apertures (see Chapters 8 and 10).

The results show that infiltration rates are low, varying between about 0.25 and 1.1 ac/h, with the majority of measurements between 0.3 and 0.6 ac/h. The fluctuations are due to changes in wind speed and direction and external air temperature, as discussed earlier.

Figure 9.8 shows a frequency distribution of all the OU measurements. The range covered is 0.25 to 1.15 ac/h, with a mean of 0.508 ac/h.

It should be remembered that the internal air temperature was artificially high to suit the heating experiments carried out during the same period - 22$^{\circ}$C for about half the data and 25$^{\circ}$C for the other half. Stack-induced infiltration rates will therefore have been higher than in the neighbouring occupied houses which had winter average temperatures of between 16$^{\circ}$C and 20$^{\circ}$C. It is reasonable to assume therefore, that infiltration rates in the

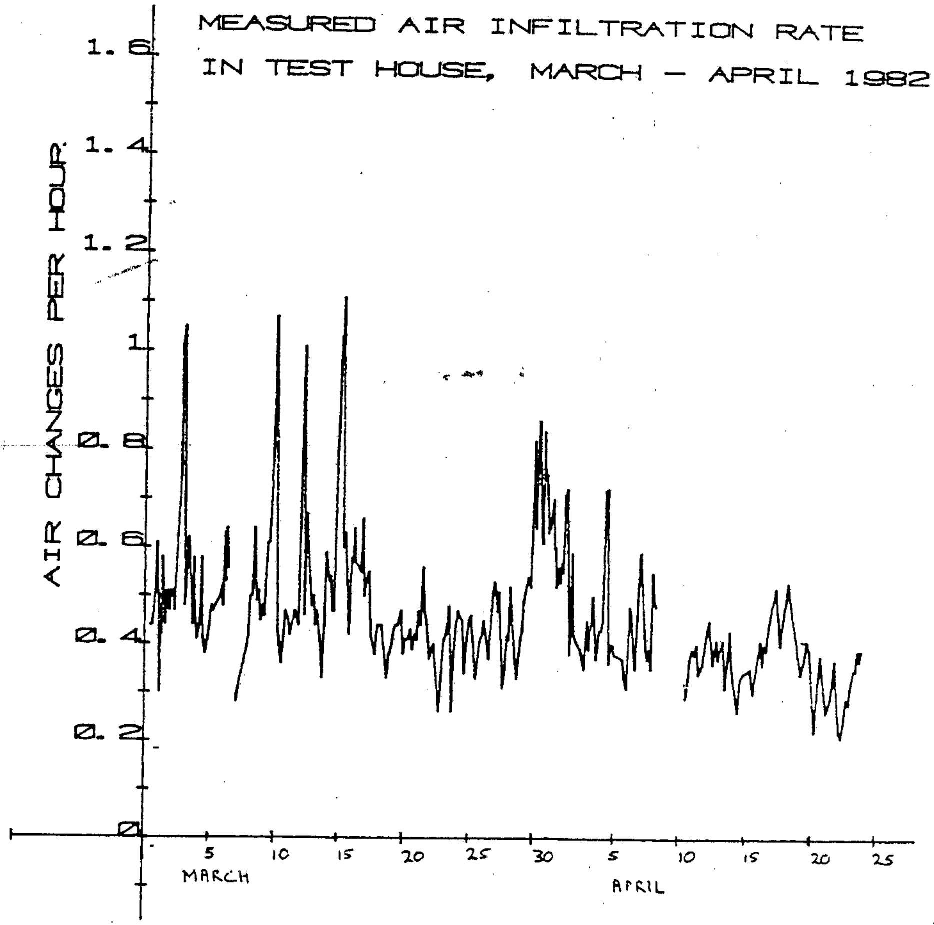



Figure 9.7

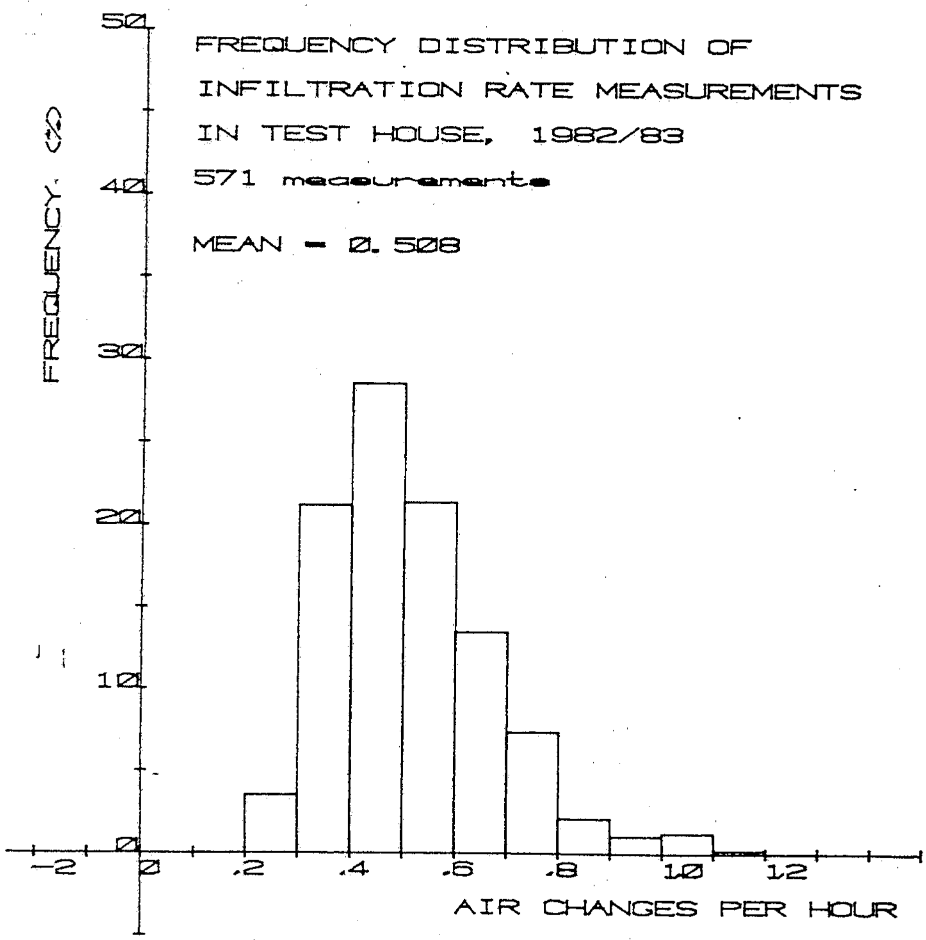



Figure 9.8

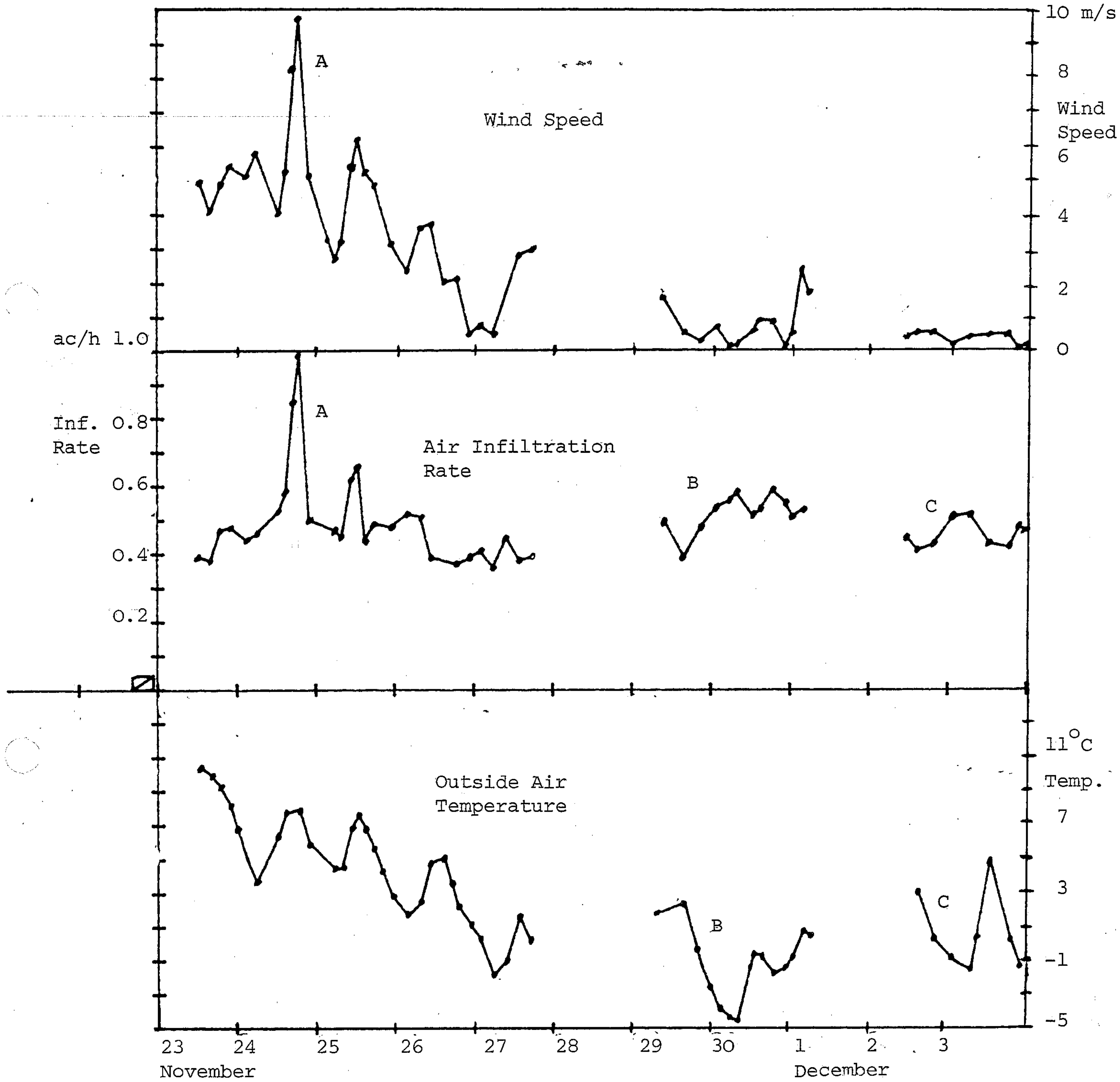



Figure 9.9 Effect of wind and stack effect on air infiltration rates

Test House measurements 1982
Internal temperature = 25°C
Wind dominated - Point A
Stack dominated - Points B and C

occupied houses will be lower, by perhaps 0.1 or 0.2 ac/h, assuming similar leakage characteristics (in fact, the occupied houses were ever tighter - see pressure tests earlier).

Houses with infiltration rates below 0.5 ac/hr can certainly be considered as well sealed. The reasons for this are discussed later.

Figure 9.9 shows a selection of data for November/December 1982, illustrating wind and stack induced effects separately. The effect of wind can be seen clearly at point A. The wind speed rises from 4 m/s to nearly 10 m/s, causing the infiltration rate to increase from about 0.5 to 1.0 ac/h. The stack effect, due to the inside-outside temperature difference, drops by about 7°C (the internal air temperature is kept constant at 22°C), causing the infiltration rate to rise from 0.4 to 0.6 ac/h. This rise is solely attributable to the stack effect, as the wind speed at this time is only 1 m/s or less, which is below the threshold of the wind-dominated region referred to earlier (about 2 m/s). A similar less pronounced effect is seen at point C.

(ii) British Gas Formula

The derivation of the formula is given in appendix 9.1. Some OU measurements are compared with predictions for the stack dominated region in figure 9.10. The agreement is fairly good, and is improved by shifting the prediction line by 15%. This may be a real difference due to the internal doors being closed for the British Gas tests while open for the OU measurements, and inadequate mixing of tracer gas for the OU measurements.

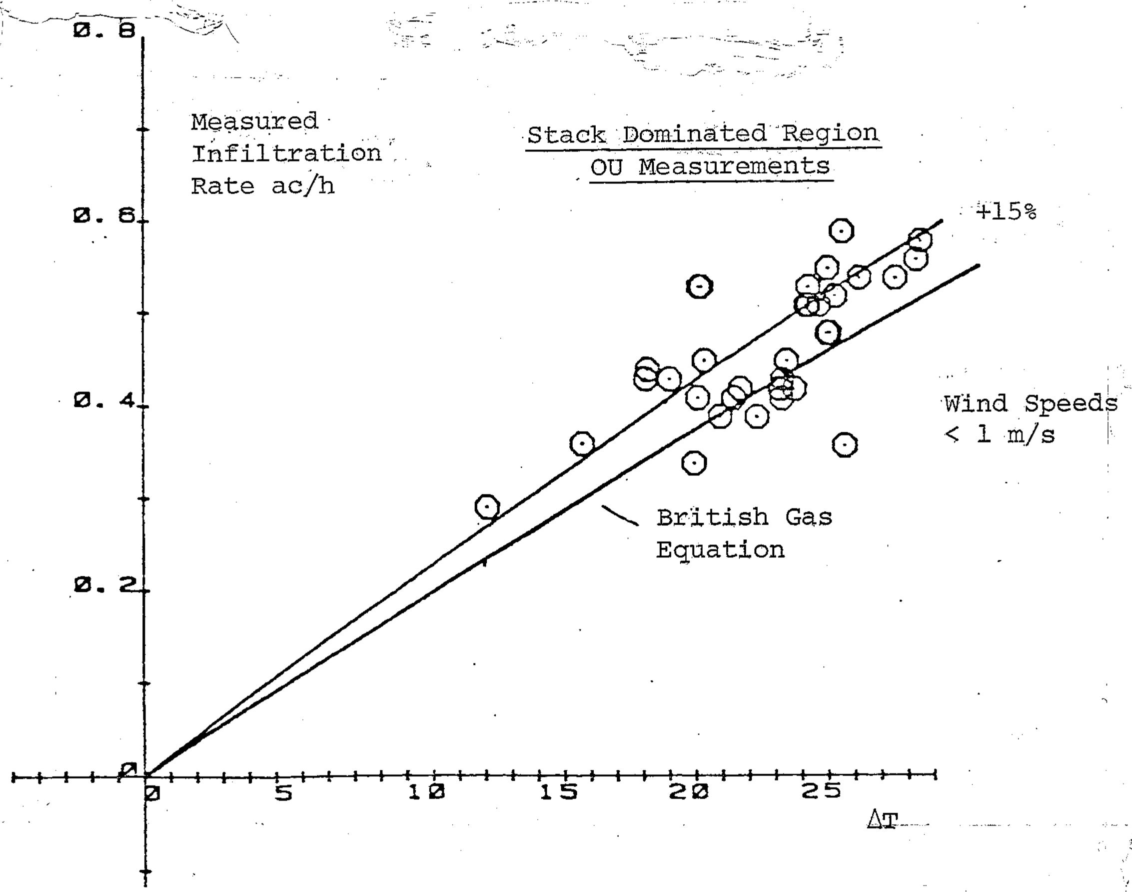



Figure 9.10 Comparison of OU measurements with British Gas prediction formula, for the stack-dominated region

(iii) Siting and orientation

Measurements in the wind dominated region revealed some interesting results for winds from different directions. The monitoring showed a marked reduction in infiltration rate caused by winds from the S.W. (see appendix 9.1 for full results).

A convenient way of illustrating this is in the form of the polar diagram superimposed on the site plan in Figure 9.11. Here the radial scale is a function of air change rate in that direction.

It can be seen that the test house is sheltered from the S.W. by the adjacent house. This results in relatively lower infiltration rates for winds from this direction. This is significant since the majority of the winds are from this direction and these include the strongest winds on this site.

The implications for energy savings due to such sheltering is discussed later.

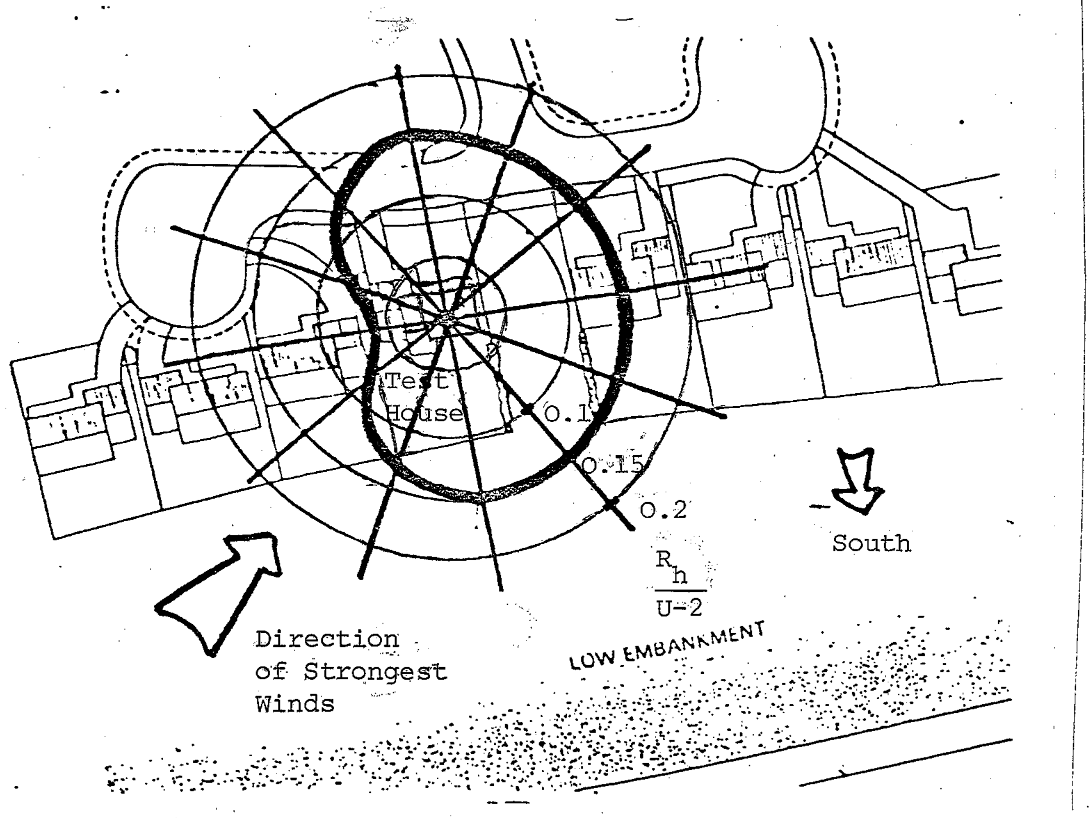



Figure 9.11 The polar diagram shows the sheltering effect of the adjacent house to the S.W.

## 9.5 Infiltration and ventilation in occupied houses

The direct measurement of infiltration and ventilation rates in the occupied houses was impossible from a practical point of view. Therefore estimates were made using the British Gas formulae, the leakage characteristics of the houses, measurements of internal temperatures and when windows were opened, and prevailing weather conditions.

### 9.5.1 Infiltration

The infiltration rate was estimated using the British Gas formulae, with a correction factor applied to take into account the different leakage characteristics of the houses. An explanation of the method and assumptions can be found in appendix 9.2.

The estimates can only be seen as crude approximations but are much more useful than assuming a constant air change rate of for example 1 ac/h.

The results are shown in Figure 9.12, plotted as daily averages over the 1982/83 heating season. The general pattern of fluctuations is very similar for each house, as they are all subjected to the same weather conditions. The absolute values are also very similar for houses 33, 36 and 38, with seasonal averages of about 0.3 ac/h. Infiltration rates for house 35, however, are lower, with a seasonal average of about 0.2 ac/h. This is because temperatures in house 35 were lower than the others - the whole-house heating season average was 16.3°C compared with 18.6°C, 18.8°C and 20.1°C - resulting in lower stack-induced infiltration rates.

### 9.5.2 Window opening

Measurements of when the occupants opened windows has produced some interesting results. Figure 9.13 shows total window-opening behaviour for four houses, expressed in terms of the average number of "open-window hours" per day for each month of the space heating season, October 1982 to May 1983. There are 11 operable windows in each house, so the maximum number of open hours per day is 264 hours.

(i) Overall patterns

For houses 36 and 38, window opening is very low and almost independant of time of year, apart from slight increases for house 38 during autumn and spring. (Closer examinations of the data for house 36 shows that the occupants tended to open the lounge and main bedroom windows regularly, almost every morning, but only for half an hour or so presumably to "clear the air").

Window opening for house 33 is equally as low during the mid-winter months, but there are sharper increases at autumn and spring.

For house 35, the pattern is highly time (and hence weather) - dependant. Values are also low during the mid-winter months, but there are dramatic increases at autumn and spring, as might well be expected; the milder, more enjoyable weather at these times of the year produces a natural

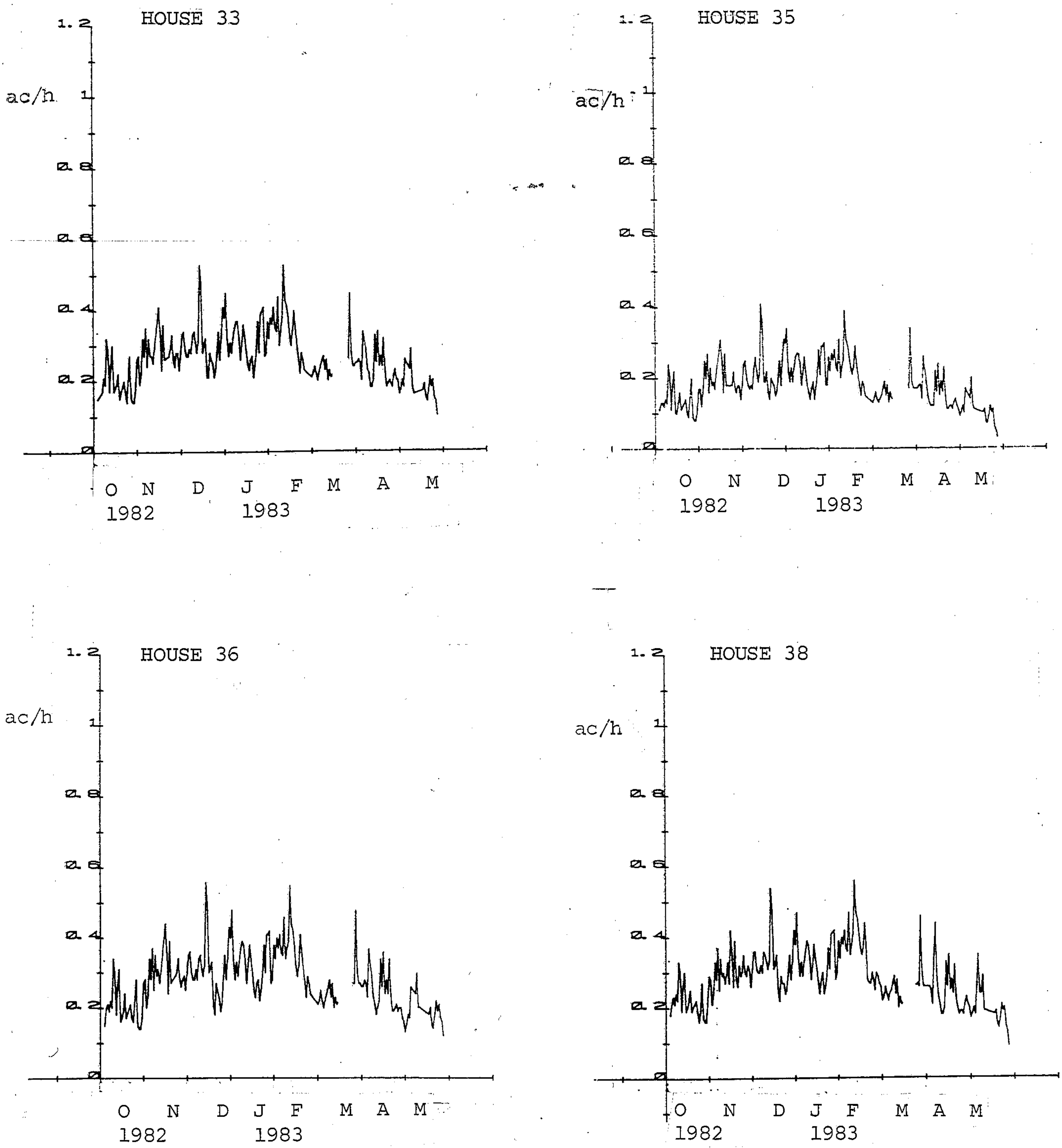



Figure 9.12 Estimated daily average air infiltration rates

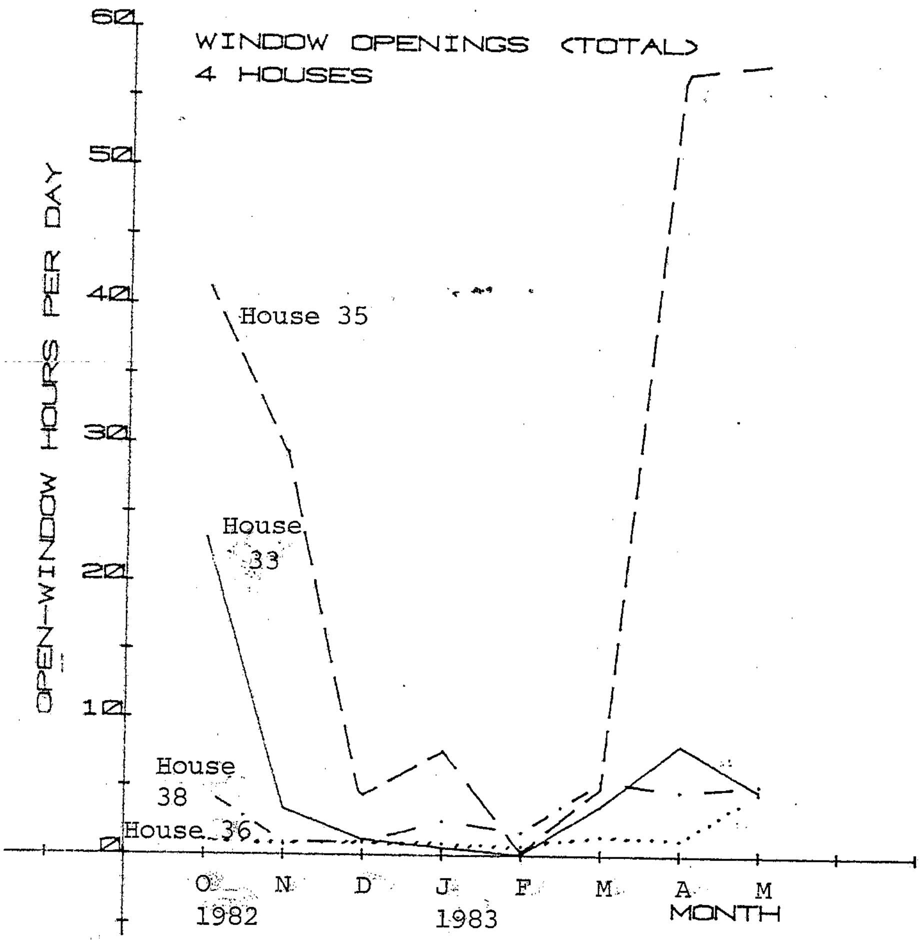



Figure 9.13 The length of time windows are open varies by a factor of ten or more

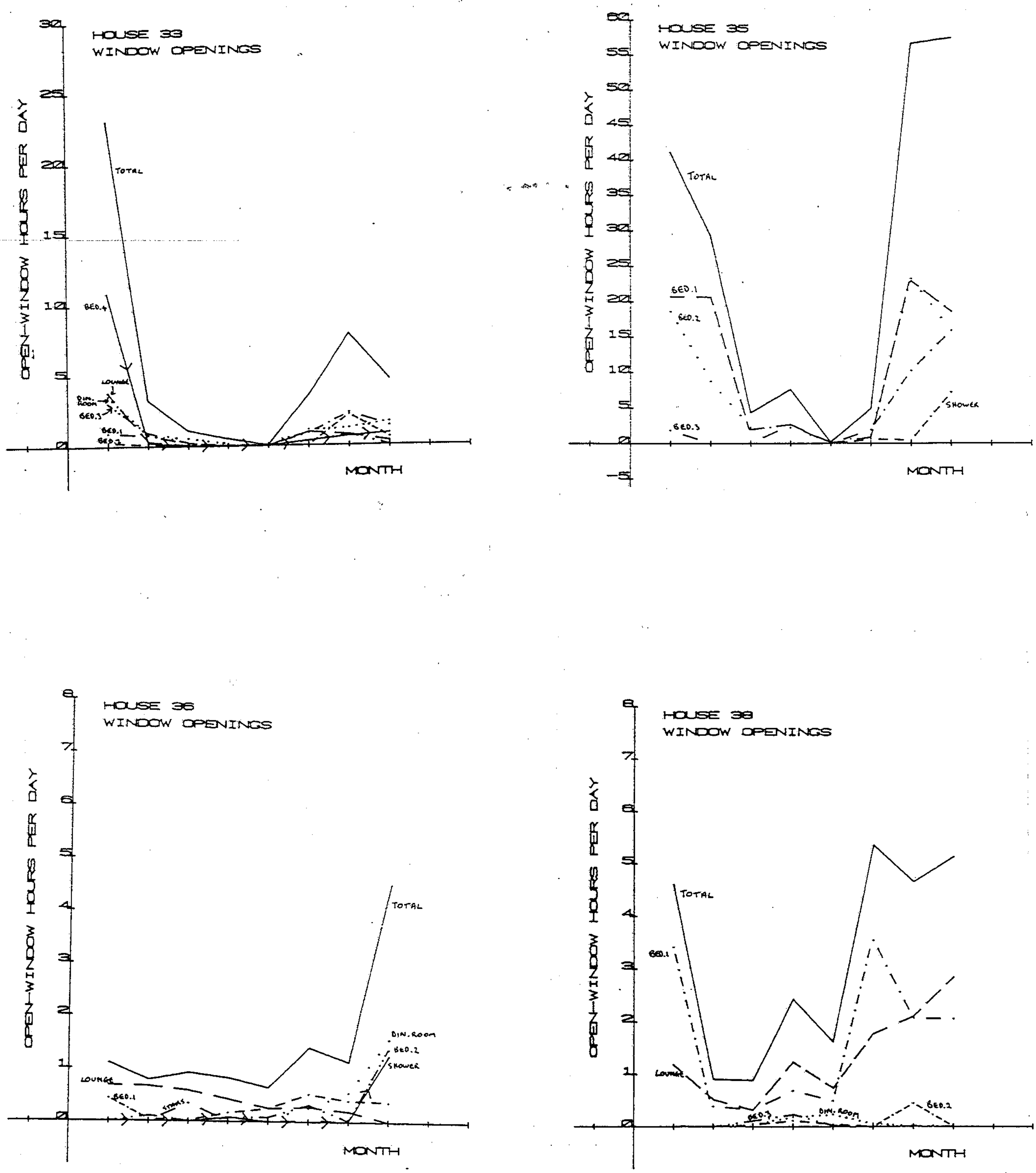



Figure 9.14 Individual room window-openings

inclination to "open the windows and let the sun and fresh air in". It is also interesting to see an increase in January, followed by a decrease again (to virtually nothing) in February, corresponding to a particularly mild January and a cold February.

(ii) Distribution

The distribution of window openings around the house is interesting (Figure 9.14). In all four cases, openings are almost entirely restricted, in varying proportions, to the lounge (except house 35), dining room and bedrooms. There are virtually no window openings at all in the kitchen, W.C., bathroom, en-suite shower-room (except for houses 35 and 36 during May) and the stairwell. This is somewhat surprising, as these rooms (with the exception of the stairwell) are areas where smells and water vapour are produced. However, no complaints were received about this, and all occupants considered that in general, they could adequately ventilate their houses using the small ventilators, the windows or the rear lobby door to the garage. Some occupants remarked that their reason for not opening the kitchen window was that it was too difficult to open.

### 9.5.3 Ventilation

Some of the measurements of air change rates carried out by British Gas in the test house included cases with various windows open. From these measurements, it was possible to extend the infiltration rate prediction equation to make crude estimates of the extra ventilation resulting from windows being opened in the occupied houses. Although it was not possible to measure the exact amount by which a window was opened, an average value of 10 cms. was assumed. A full description of the method and assumptions is given in Appendix 9.2.

Figure 9.15 shows the results of including hourly window-opening data for four houses in the prediction formula, to give estimates of total ventilation rates, expressed as daily averages over the heating season. These should be compared with the estimates of infiltration rates in Figure 9.12.

As windows are opened very little in houses 36 and 38, there is very little extra ventilation and the air change rates are only very slightly higher than the infiltration rates. This is largely true for house 33, except for October when air change rates increase by 0.3-0.4 ac/h due to a relatively high level of window opening. In house 35 there are substantial increases in air change rates during spring and autumn due to the high level of window opening.

Averaging the data in figures 9.12 and 9.15, estimates of the seasonal average infiltration and ventilation rates are:

| House | Infiltration ac/h | Extra Ventilation ac/h | Total ac/h |
|---|---|---|---|
| 33 | 0.27 | 0.04 | 0.31 |
| 35 | 0.18 | 0.19 | 0.37 |
| 36 | 0.28 | 0.02 | 0.30 |
| 38 | 0.29 | 0.02 | 0.31 |
| | 0.26 | 0.06 | 0.32 |

### 9.5.4 Heat losses

The effect of these infiltration and ventilation rates on energy consumption will, of course, depend on the temperature difference between inside and outside.

In houses 36 and 38 the heat loss through infiltration and ventilation increases with temperature difference in mid-winter (see Figure 9.16). In house 33 the heat losses are more uniform throughout the heating season - the smaller temperature difference at the ends of the season being offset by high ventilation rates. But in house 35 the high ventilation rates during the spring and autumn have resulted in higher heat losses at the ends of the season.

The results are interesting in that they illustrate how different people's behaviour can dramatically affect infiltration and ventilation rates and thus energy consumption.

### 9.5.5 Infiltration, ventilation and energy consumption

Table 9.5 gives the estimated ventilation and infiltration losses for the heating season (October - April) for each house, as a proportion of the total heat loss. Despite the commonly-held belief that infiltration and ventilation heat losses are a large proportion of the total for a highly insulated house, these estimates show that the proportion is quite low - between 11 and 15%. This is entirely due to the fact that the houses are much better sealed than was assumed. Had infiltration rates been 1 ac/hr as was originally assumed, rather than 0.2-0.5 estimated in practice, the proportion would have been nearer 40%.

The estimates described in this section are obviously crude, and the method of estimation does not take into account ventilation through open doors (i.e. french windows, front door, and rear lobby door to the garage). Perhaps it would be fairer to say that infiltration and ventilation heat losses are estimated as "20% or less" of the total heat losses.

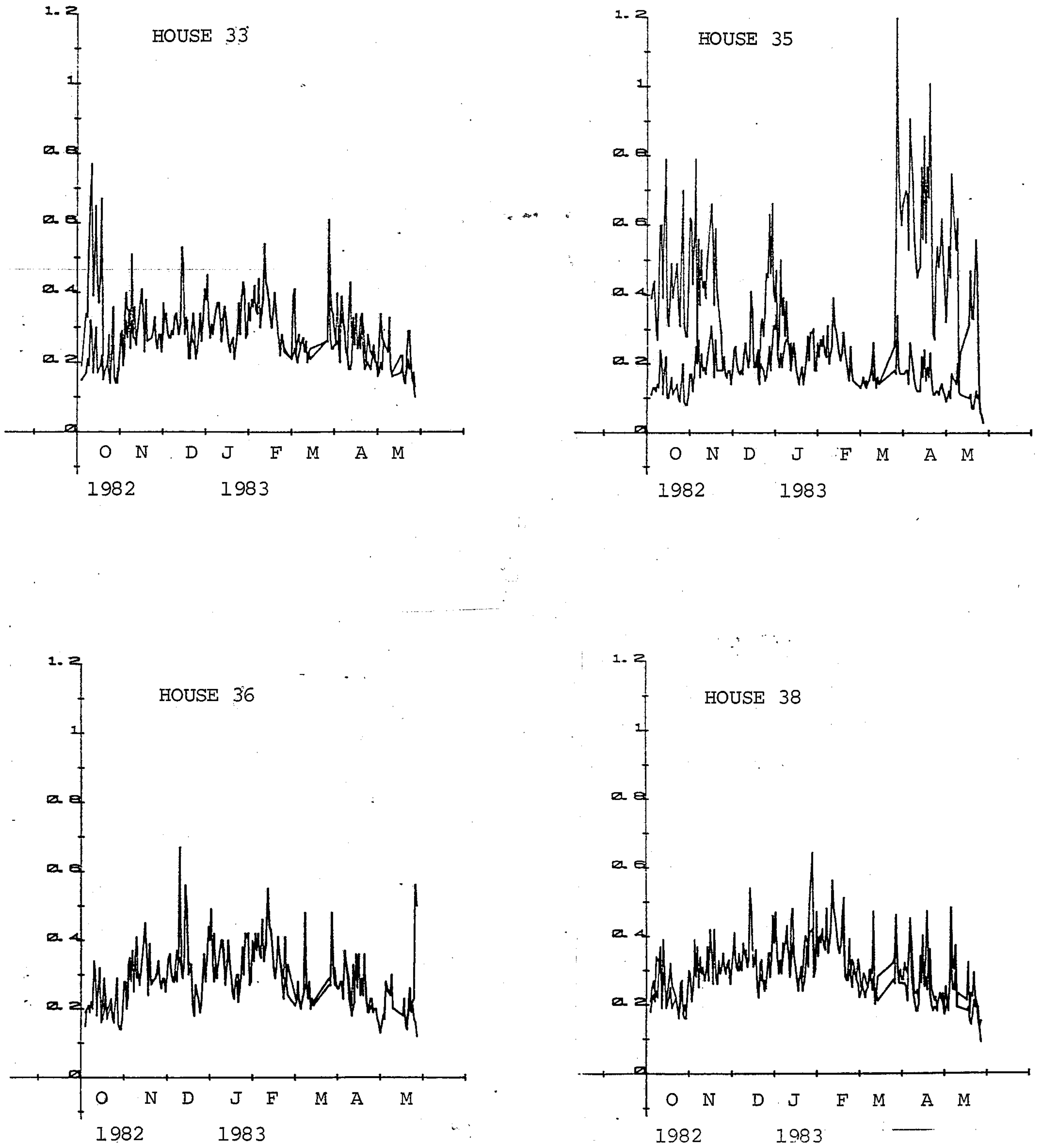



Figure 9.15 Ventilation increases air changes above infiltration rates in house 35 but has little effect in houses 33, 36 and 38

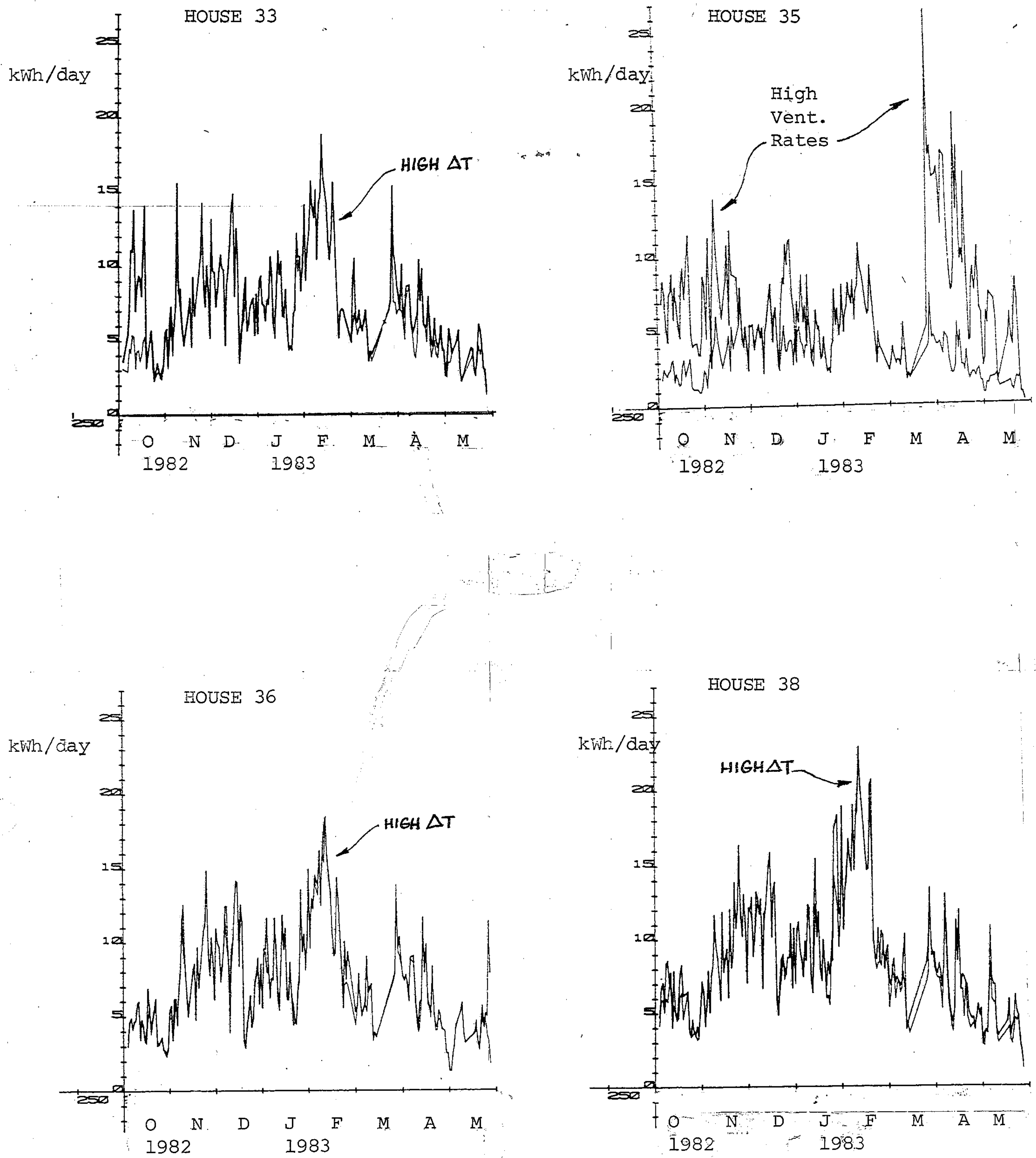



Figure 9.16 Ventilation heat losses depend on air change and temperature difference

Table 9.5 Estimates of infiltration and ventilation heat losses as a proportion of the total

| House | Infiltration heat losses | Extra ventilation heat losses | Total | % of total house heat loss |
|---|---|---|---|---|
| | kWh | kWh | kWh | % |
| 33 | 1516 (87%) | 225 (13%) | 1741 | 13 |
| 35 | 846 (55%) | 692 (45%) | 1538 | 15 |
| 36 | 1547 (97%) | 48 (3%) | 1595 | 12 |
| 38 | 1845 (98%) | 40 (2%) | 1885 | 11 |

## 9.6 Design considerations

The low infiltration rates achieved in the Linford houses are the result of a number of factors: siting, orientation and shelter; internal planning and layout; and the constructional details.

The energy implication of low infiltration rates are significant. If these houses had rates typical of the general new housing in the UK, then the useful energy consumption would have increased by typically 1000-1500 kWh/yr (see Chapter 6), equivalent to an extra 30% or £20 on the space heating fuel bill. Therefore it is worthwhile examining some of the reasons how these low infiltration rates have been achieved.

### 9.6.1 Siting, orientation and shelter

The Linford site is of moderate exposure as can be seen from the wind data in Figure 9.17. The maximum hourly average wind speed recorded during the 1982/3 heating season was less than 12 m/s. The prevailing winds blow from the south west, as can be seen in Figure 9.18. There is a certain amount of natural shelter from the planting to the south of the houses.

However the main sheltering effects are due to the positioning of the houses relative to one another and also the fact that the houses have no windows in their side walls. The test house results show a marked reduction in infiltration from westerly winds because it is sheltered by the adjacent house and the wind is not broadside on to the main glazed areas. The effects of wind parallel to the row of houses can be seen in figure 9.19.

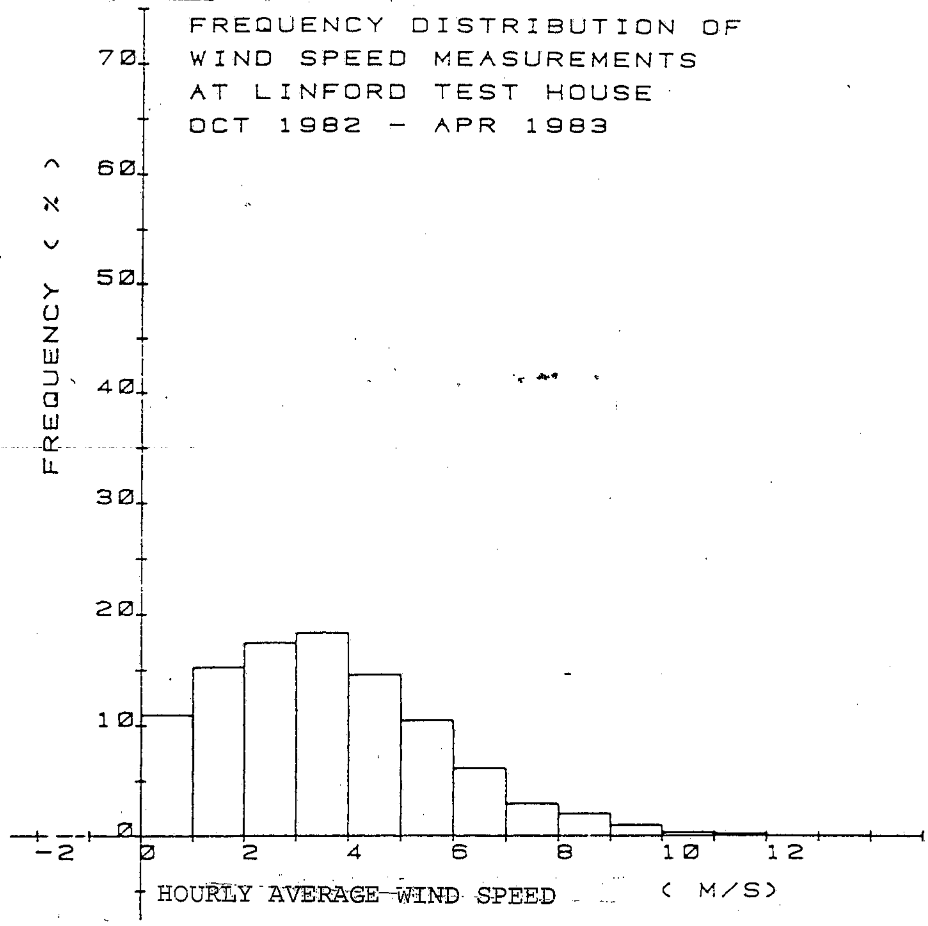



Figure 9.17

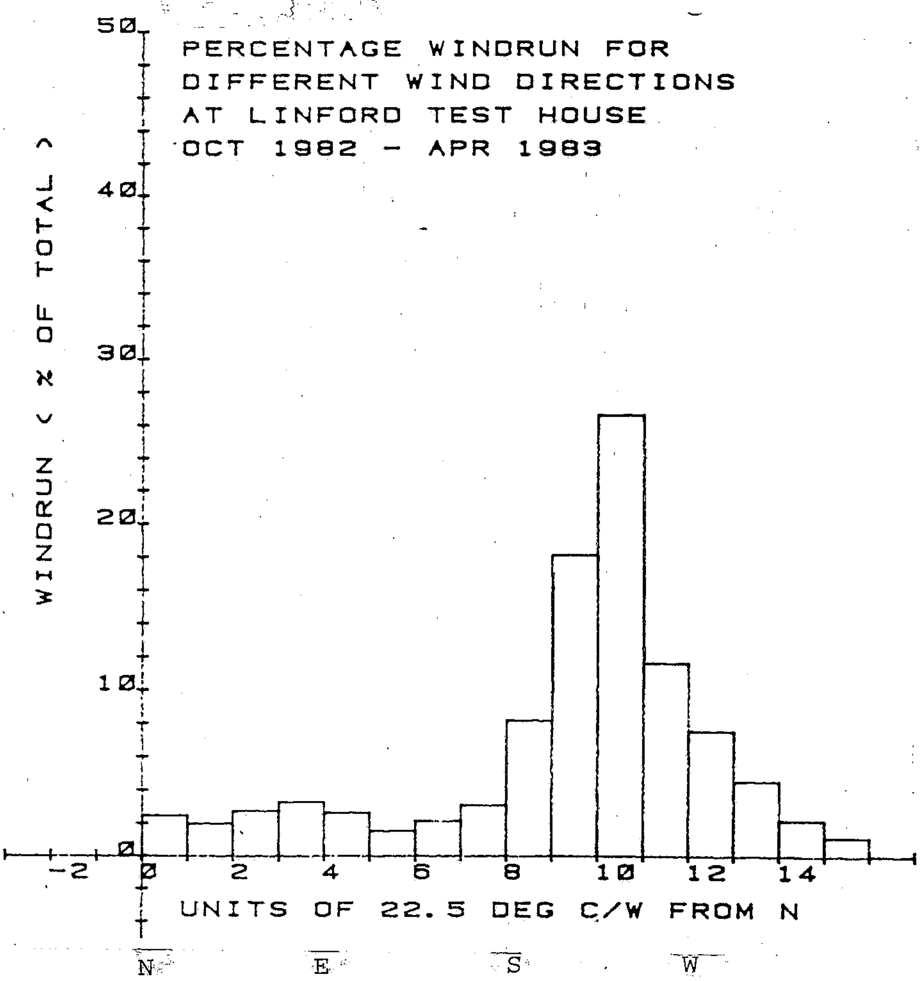



Figure 9.18a

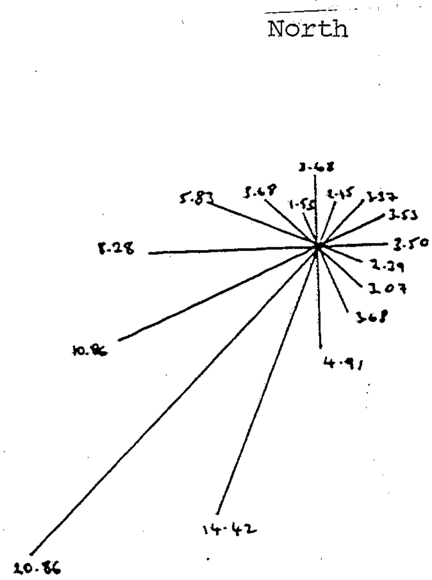
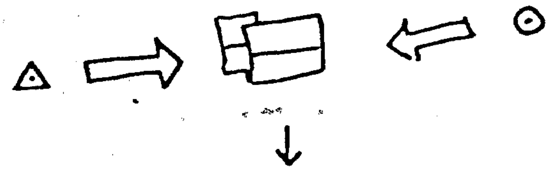



Figure 9.18b Wind Rose – % of time that wind is in given direction



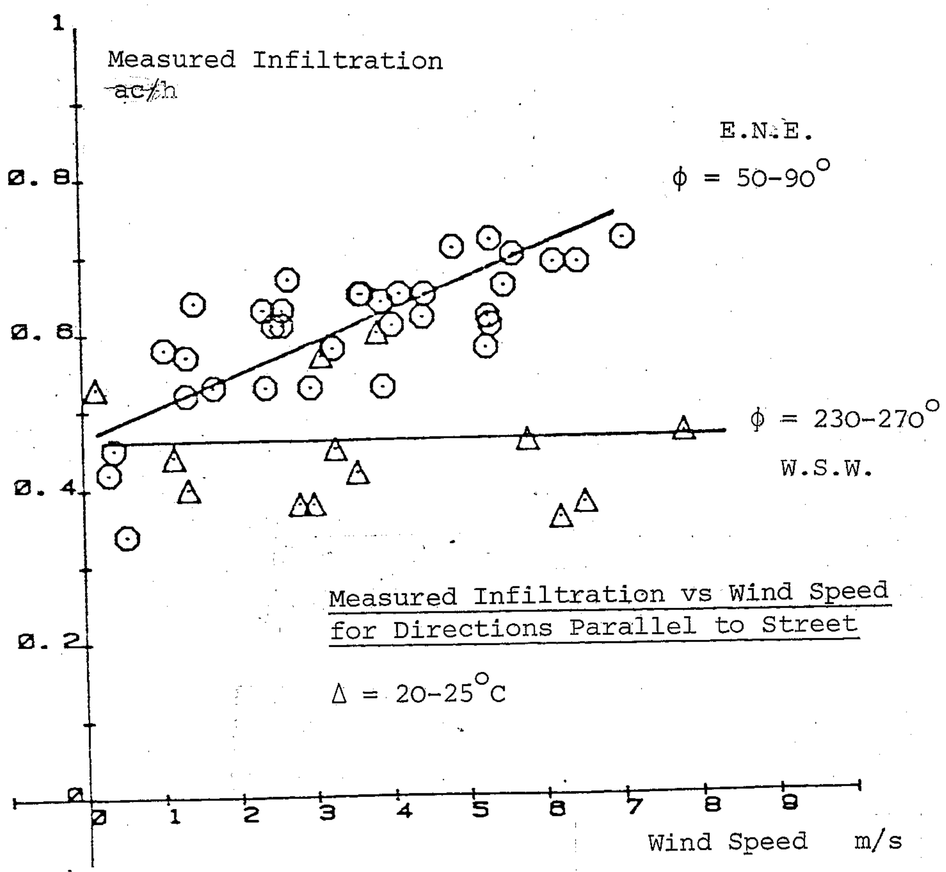




Figure 9.19 Strong winds from the W.S.W. do not increase infiltration as much as winds from the more exposed E.N.E.

Increased wind speed from W.S.W. result in little or no increase in infiltration but from the E.N.E. there is an increase in infiltration rate as wind speed increases. This is an important effect because south westerly winds predominate on the site (see Figures 9.17 and 9.18).

Having established this effect in the form of a polar diagram it is possible to predict roughly the effect of this sheltering on energy consumption, as shown in Figure 9.20.

As the site exists the average seasonal infiltration rate for the test house is about 0.32 ac/h. If an internal temperature of 19°C is assumed this results in a seasonal loss of 1826 kWh. If the house was not sheltered to the S.W. these prevailing winds would increase infiltration to 0.42 ac/h with a resulting increase in energy consumption of about 440 kWh/yr.

Improving the shelter from the N.E. has little effect, though the position of the estate on a southerly slope may imply some sheltering from the N.E. anyway.

So the lessons which seem to be emerging from these results and projections are:

i) shelter from the strong prevailing S.W. wind is important and worth around 440 kWh/yr in this instance.

ii) shelter from the cold N.E. winds is less important because they are less frequent and not so strong. They are also usually associated with colder temperatures when stack effects will dominate.

These conclusions are reinforced by a practical experiment in the Twin Rivers field trial in the USA. There a shelter belt of mature trees was planted to the windward of a row of houses. This produced an estimated reduction of infiltration rate of 0.2 ac/h (Reference 9.3).

### 9.6.2 Internal planning and layout

Any openings which face into the prevailing wind are obviously liable to lead to higher infiltration rates. The Linford houses have been designed with lobbied entrances which face N.W. (Figure 9.21). The lobbies are of a reasonable size to allow the outside door to be shut before the inside door is opened. But the french windows off the living room in the Linford houses are not a desirable feature, from the air tightness point of view. They required extensive draught stripping to cut down on leakage. A better solution was achieved at Pennyland where access on the south side has been provided with a draught lobby.

In both designs the stairs are isolated from the warmer living spaces. This reduces stack induced infiltration.

### 9.6.3 Constructional details

The low infiltration rates are somewhat surprising given that the houses are of fairly standard construction. The only details which are thought to have

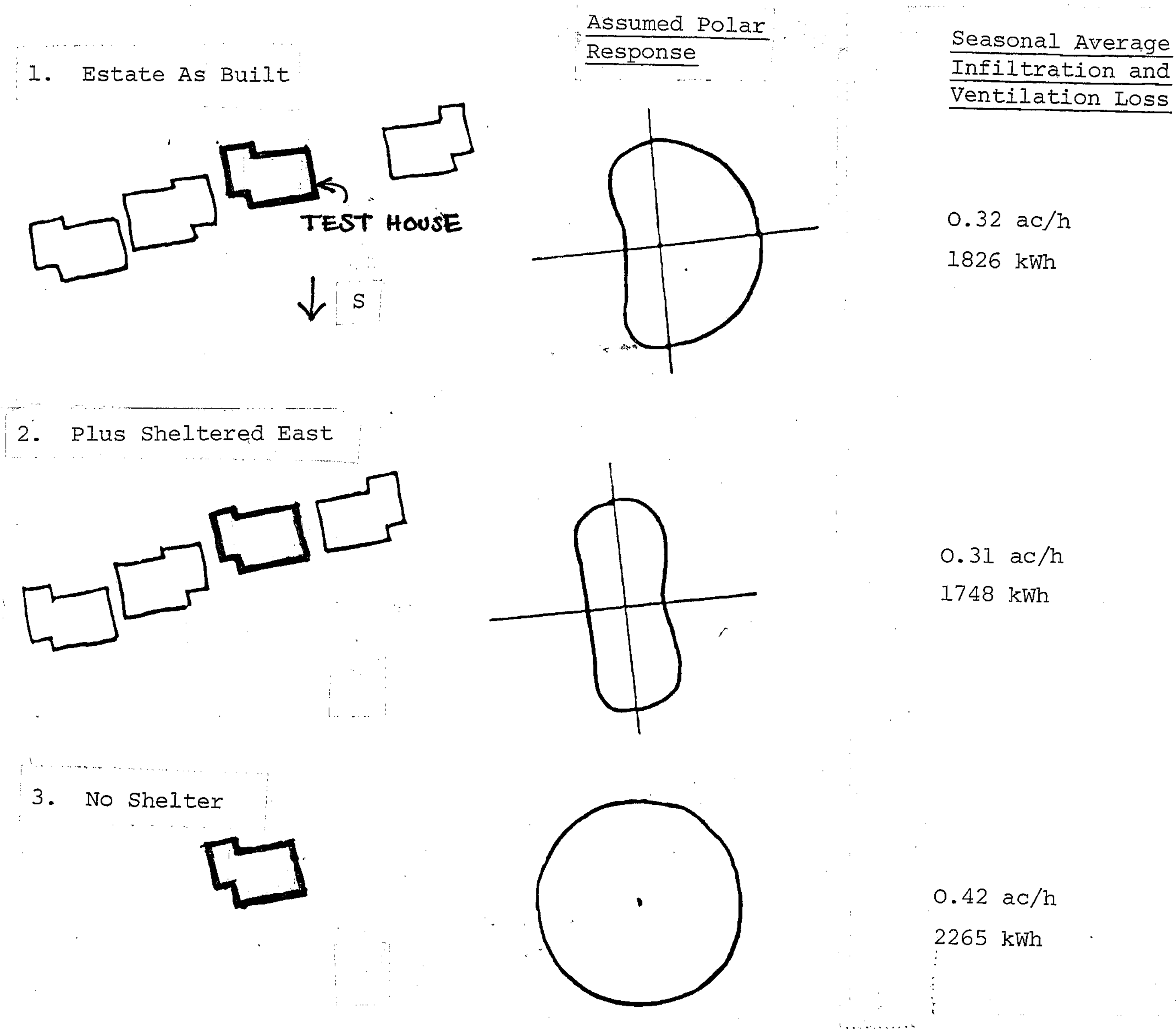
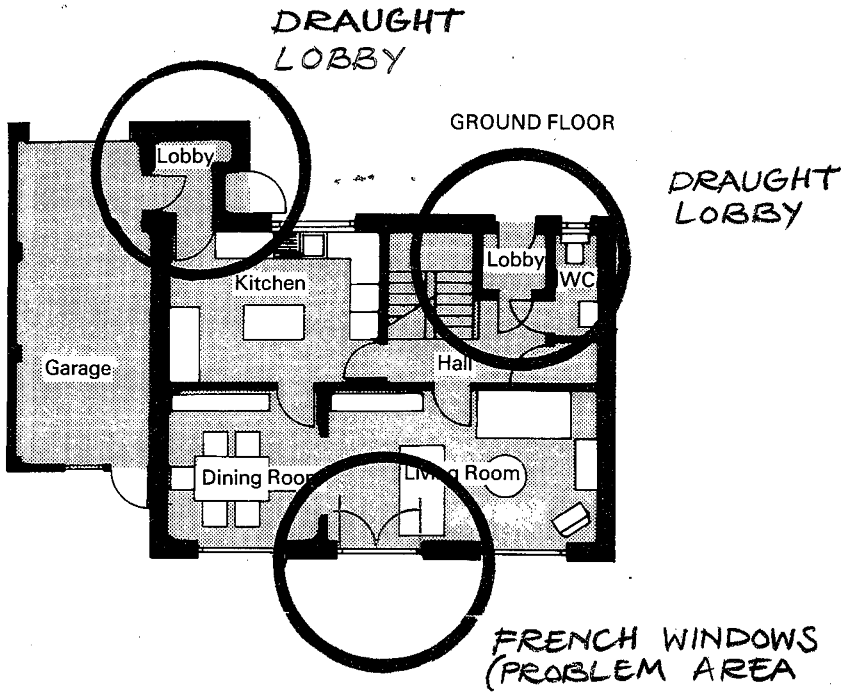



Figure 9.20 Possible effects of estate layout on air infiltration rate and seasonal energy consumption

Assumed $T_{in} = 19^{o}C$

**LINFORD**

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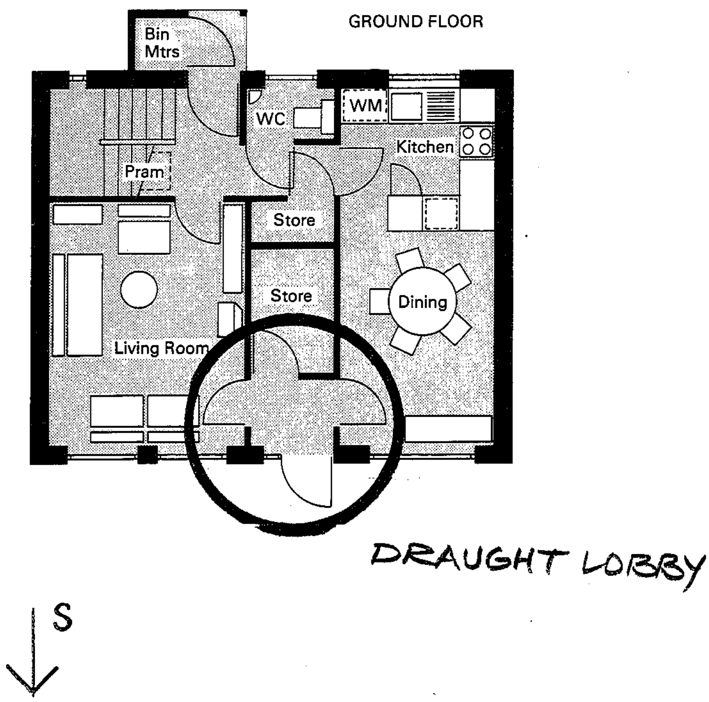



Figure 9.21 Internal planning is important in the reduction of infiltration

reduced air leakage are:

i) The window design which seems to perform well. The large glass areas mean that there are less cracks than there would be around normal opening sash or casement windows.

ii) The glass fibre cavity wall insulation which probably results in less leakage into the house via the cavity. This is despite the fact that the first floor is suspended from the internal blockwork leaf in the normal way.

iii) The cavity closers which appear to form a 'tight' seal between the window and door frames and the walls.

iv) Another detailing problem, which was highlighted by the pressurisation tests, was the treatment of the soil and vent pipe. Attention needs to be paid to the method of encasing this pipe in the house and to the detailing where it passes through the ceiling and roof. Poor detailing can create a leaky duct passing right through the house.

v) The use of a balanced flue boiler.

## 9.7 Conclusions

1. The houses were much more airtight than was expected.

2. Pressurisation tests showed that leakage areas were considerably smaller than "normal" U.K. houses.

3. Measured infiltration rates in the test house varied between 0.2 and 1.2 ac/h, and were typically 0.4-0.5 ac/h.

4. The monitoring in the test house enabled a theoretical model to be developed for the prediction of infiltration and ventilation rates in the test house, which could be extended for the occupied houses.

5. Window opening during the mid-winter months was very low. Only in one house did the level of window opening during spring and autumn lead to substantial increases in air change rates above background infiltration rates.

6. Average air change rates (infiltration + ventilation) in the occupied houses during the space heating season are estimated as between 0.3 and 0.4 ac/h, assuming a typical window opening of 10 cm.

7. Heat losses due to infiltration and ventilation were estimated as below 20% of the total energy consumption.

8. While the construction was generally tight, problems were experienced with the french window doors which had to be extensively draught-stripped, and in some cases re-hung. The windows were well sealed.

9. The effect of sheltering was found to be important. Sheltering from the strong prevailing S.W. winds was estimated to be worth kWh/yr.

## Appendix 9.1

### Infiltration Rate Measurements

These fall into two groups, those made by British Gas and those made by the O.U. Both sets were only made on the test house.

#### A9.1.1 British Gas tests

These were made over a short period during November and December 1981. They were made with their 'Autovent' microprocessor controlled system. This attempts to maintain a constant level of the nitrous oxide tracer gas in all the zones of the house. This effectively allows the determination of individual room infiltration rates, though most results relate to whole-house values.

From these measurements a general descriptive equation was derived relating infiltration to house inside-outside temperature difference $\Delta T$, wind speed U, and direction $\emptyset$. This is described in reference 9.4.

This equation has been used to determine infiltration rate given measured values of $\Delta T$, U and $\emptyset$ for the test house over the 1982/83 heating season for thermal calibration purposes and comparison with the O.U. measurements. It has also been used to give estimates of ventilation rates in the occupied houses, on the assumption that they have very similar characteristics.

#### A9.1.2 O.U. tests

These involved a simpler measurement rig adapted for continuous automatic operation (see monitoring equipment section). This used the principle of the measurement of the rate of decay of a fixed injected concentration of nitrous oxide gas.

Although the measurements are not of the same quality as the British Gas ones they were made over a much longer period, though not continuously, from February to April 1982 and November 1982 to March 1983.

The 82/83 data set has been the most useful, having complete wind speed and direction measurements, allowing a certain filling in of missing regions of British Gas measurements.

#### A9.1.3 Theory and comparisons

Infiltration is determined by three weather factors, $\Delta T$, U & $\emptyset$. At low wind speeds ($U<2$ m/s) it is solely a function of $\Delta T$. This is known as the Stack or Buoyancy Dominated region.

In this region the infiltration is due to the tendency of warm air to rise, sucking in new air into the house as it does so. The relation of infiltration to $\Delta T$ is of the general form

$$Rh = A.\Delta T^n$$

where n is somewhere between 0.5 and 1, depending on the size of cracks.

The prediction equation used a formula of the form

$$Rh = A.\sqrt{\Delta T} + B.\Delta T$$

Figure A9.1.1 shows the fit of this equation to British Gas measurements and Figure A9.1.2 to O.U. measurements from the 1982/83 data set.

At higher wind speeds infiltration becomes dependent on both U and Ø.

Because of the sheltering effect of the adjacent houses, infiltration can be described as dependent on the product of a wind function f(U) and a direction function or polar diagram (f(Ø)).

The relation f(U) can be determined by looking at infiltration rates at high wind speeds and low values of $\Delta T$ over a very restricted range of wind directions. This gave an approximate relation

$$Rh = K.(U-2)$$

This is illustrated in figure A9.1.3.

A more general curve of the form

$$Rh = A.\sqrt{U} + B.U$$

was incorporated in the prediction equation to include the non-linearity at low wind speeds.

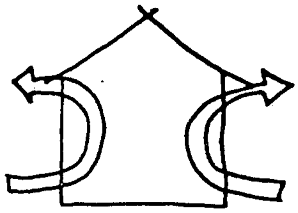
Given then, that Rh = K.(U-2).f(Ø) at high wind speeds, we can determine f(Ø) by plotting Rh/(U-2) against Ø. This is shown in Figure A9.1.4.

The cosine curve was derived from British Gas measurements. Unfortunately, these, being made over only a short period of time, only encountered a limited range of wind directions. The plot has therefore been extended using O.U. measurements over the period November 1982 to April 1983. These have been scaled by 15% to bring them into line with the British Gas measurements (see below). Although they are not of the same quality as the British Gas they do reinforce the findings of a pronounced sheltering to the West.

There does not appear to be an equivalent amount of sheltering to the East. This would appear to be due to the large gap between the test house and the next house to the East. This can be seen more clearly when the polar diagram is plotted out on an estate layout (Figure A9.1.4). Plots of Rh against U for winds parallel to the street show completely different characteristics from the East and the West (see Figure A9.1.5).

### A9.1.4 Intermediate region

Between the buoyancy dominated and wind dominated regions there is some kind



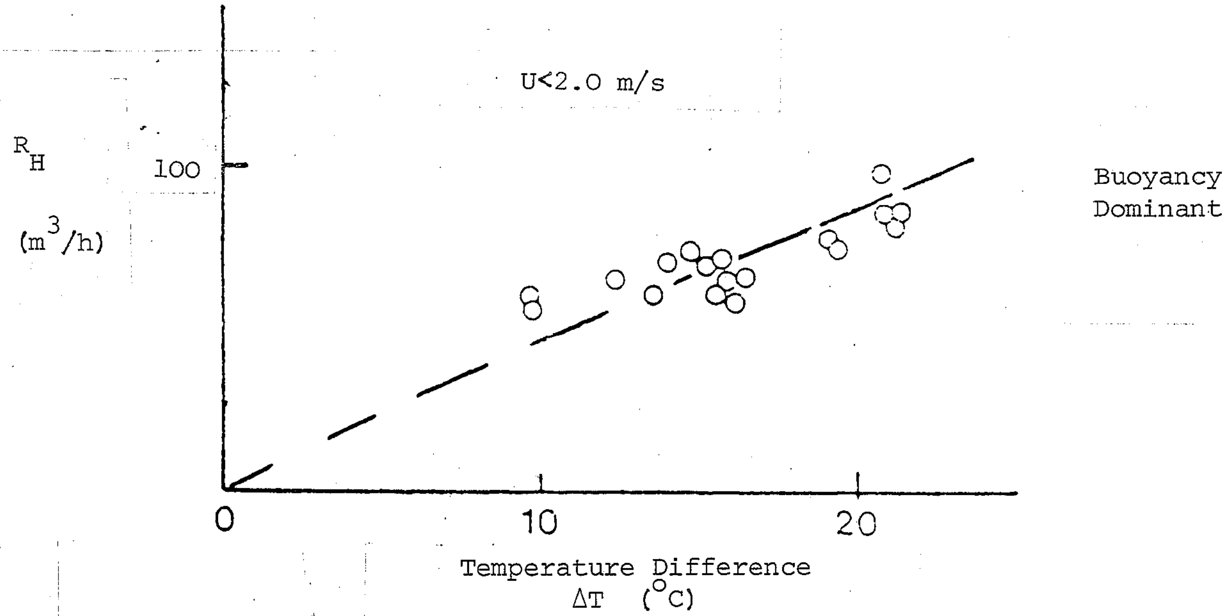



Figure A9.1.1 Prediction equation fitted to British Gas measurements

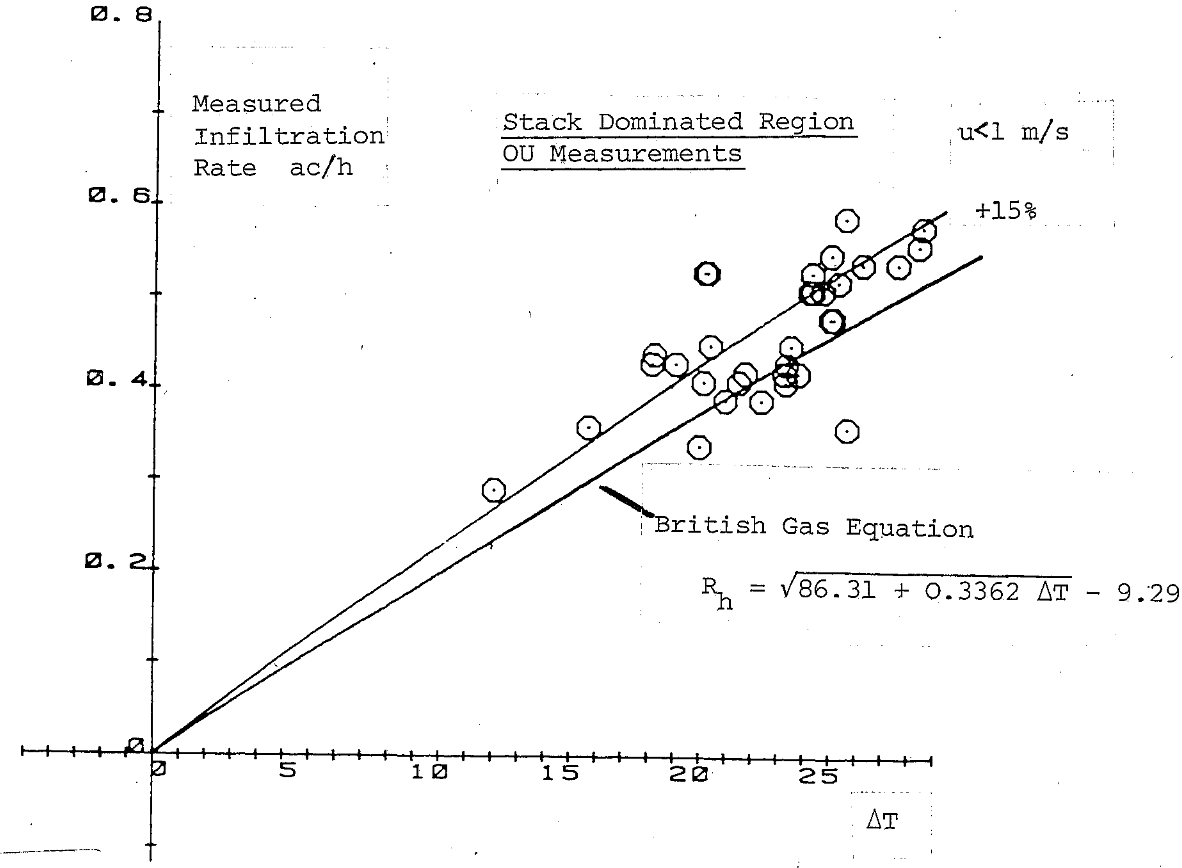
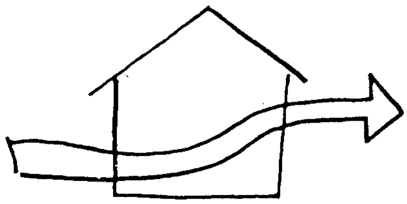



Figure A9.1.2 All measurements compared with British Gas prediction equation



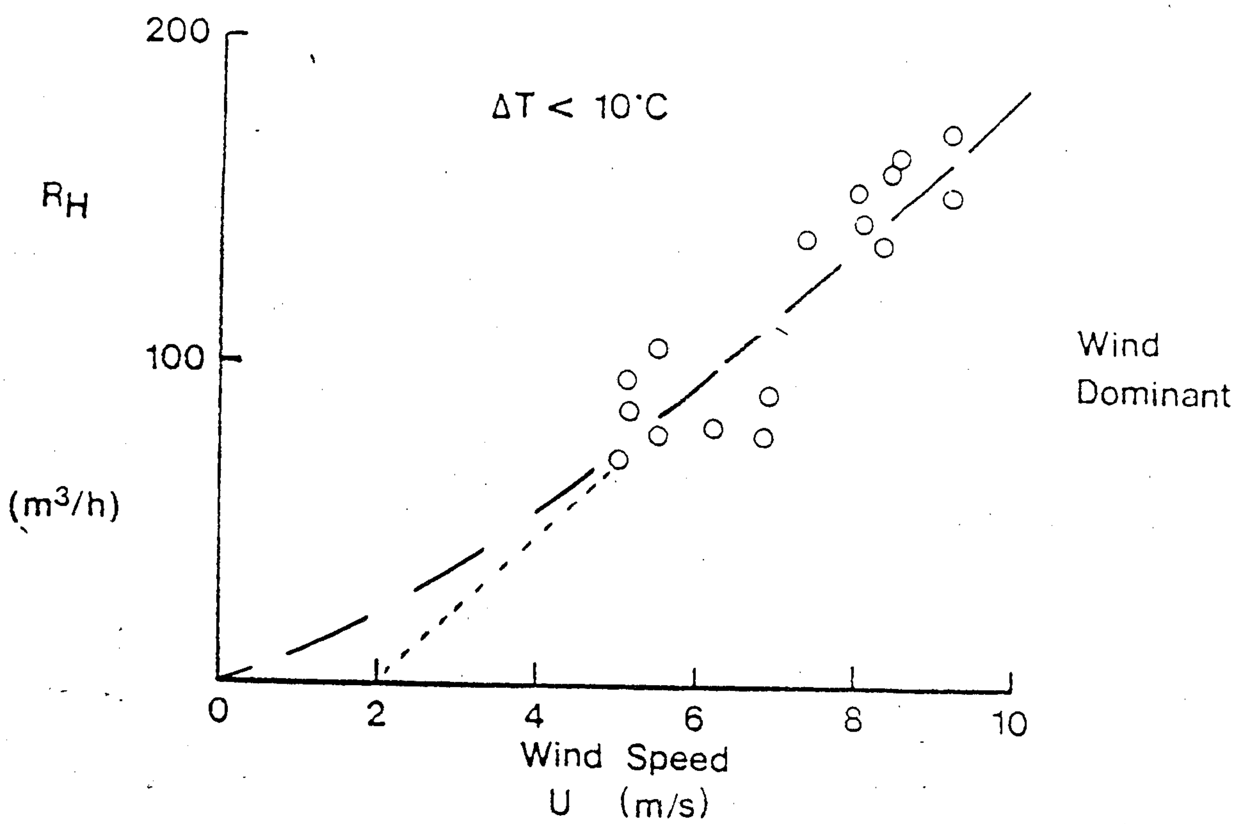
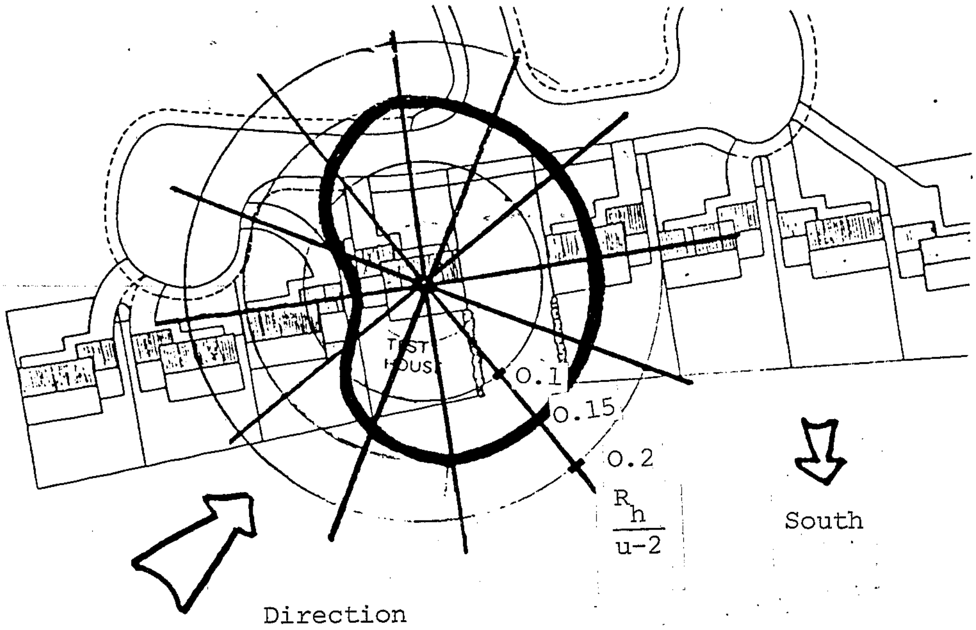



Figure A9.1.3 Determination of wind function f(u)

SHELTERING EFFECT OF ADJACENT HOUSES



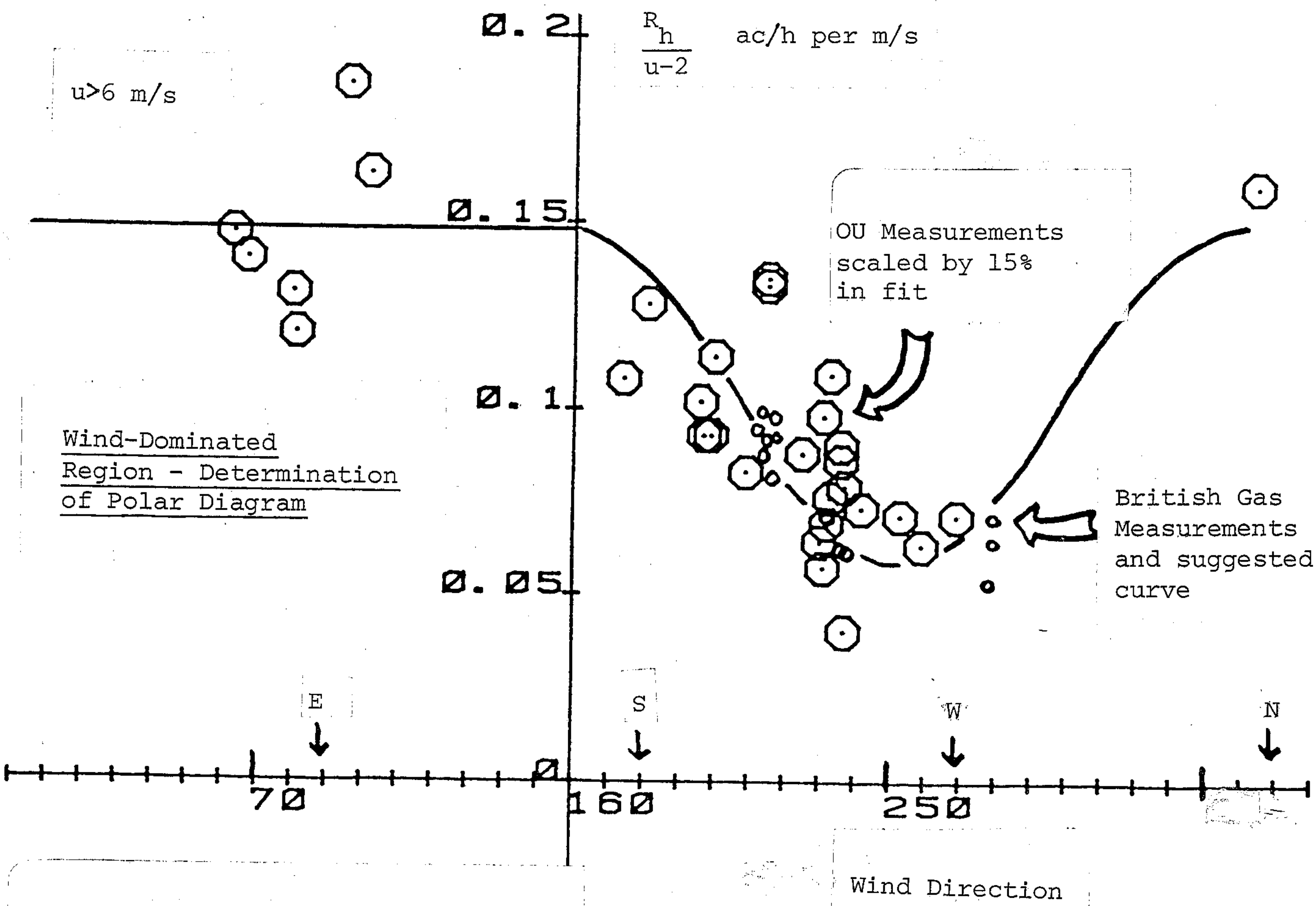
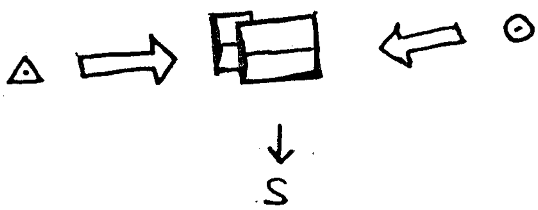




Figure A9.1.4 Sheltering effect of adjacent houses



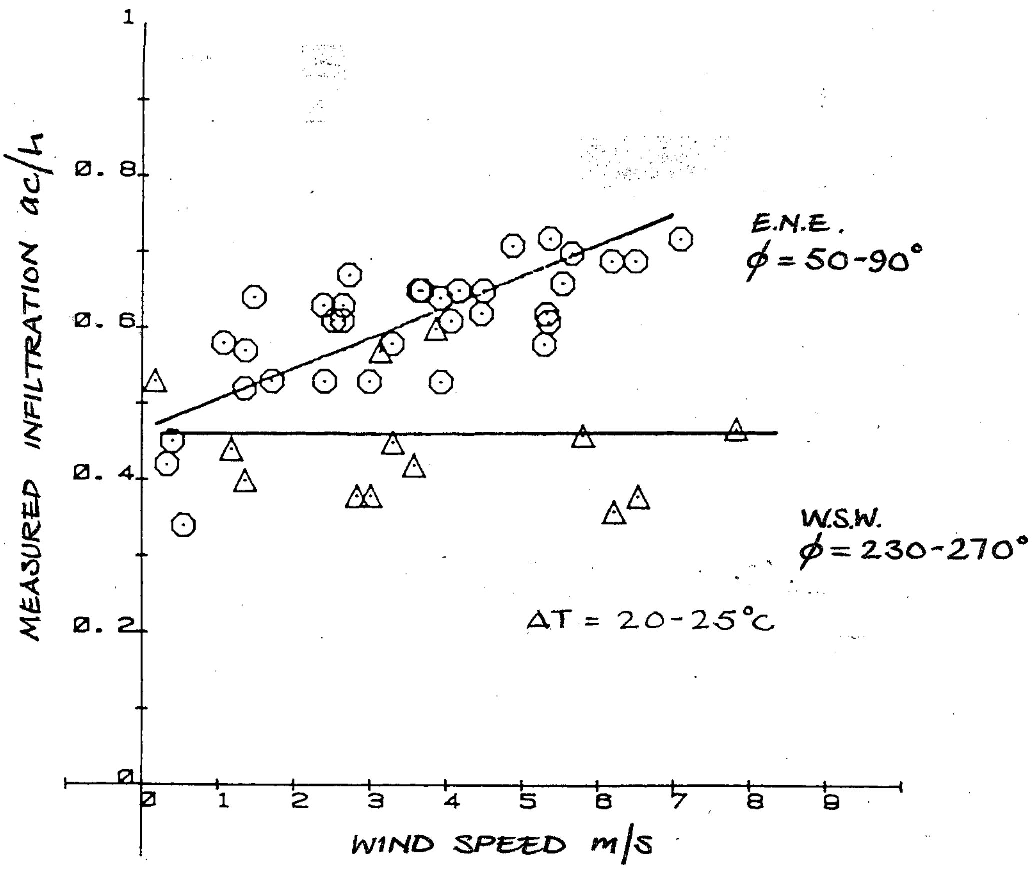




Figure A9.1.5 Measured infiltration rates at different wind speeds, for direction parallel to street. The house is sheltered to the west, but not to the east.

of smooth transition. For the purposes of the prediction model this has been achieved by linear interpolation on either side of a wind velocity V, the intersection at a given $\Delta T$ of the wind and buoyancy dominated regions.

The general relation of Rh with $\Delta T$, U, and $\emptyset$ can be described as a three-dimensional surface as in Figure A9.1.6.

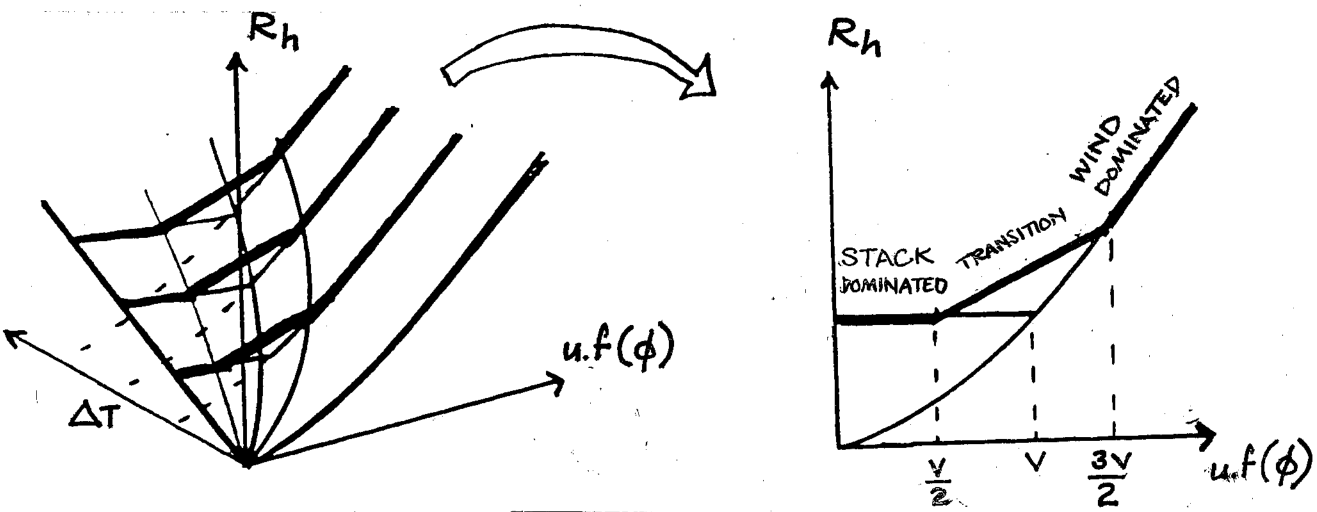



Figure A9.1.6 Relationship of infiltration rate $R_h$ with temperature difference $\Delta T$, wind speed u, and direction $\phi$

A9.1.5 Comparison of prediction and measurements

The full predictive equation used for the test house measurements has been:

buoyancy dominated region

$$Rh = \sqrt{86.31 + 0.3362.\Delta T} - 9.29 \quad a/c$$

wind dominated region

$$Rh = (\sqrt{0.193 + 0.0128.U} - 0.4393).\ f(\emptyset)$$

where $f(\emptyset) = 1.16 + 0.478.\ \cos(2\emptyset - 320)$

for $160<\emptyset<320$

$f(\emptyset) = 1.638$ otherwise

This equation has been used to predict the test house infiltration from measured $\Delta T$, U and $\emptyset$ for approximately 250 data points for which O.U. measurements are available over the 1982/83 heating season. The comparison of prediction with measurements is shown in Figure A9.1.7. This indicates a reasonable agreement, though there is a general shift of about 15%. This is probably a real effect since the British Gas equation was derived from measurements made with the internal doors closed and the O.U. measurements with them open. There may also be errors in the O.U. measurements due to inadequate mixing of air and tracer gas.

Accepting the 15% shift, it would appear that the formula can reliably predict the infiltration rate to within $\pm$ 0.2 ac/h.

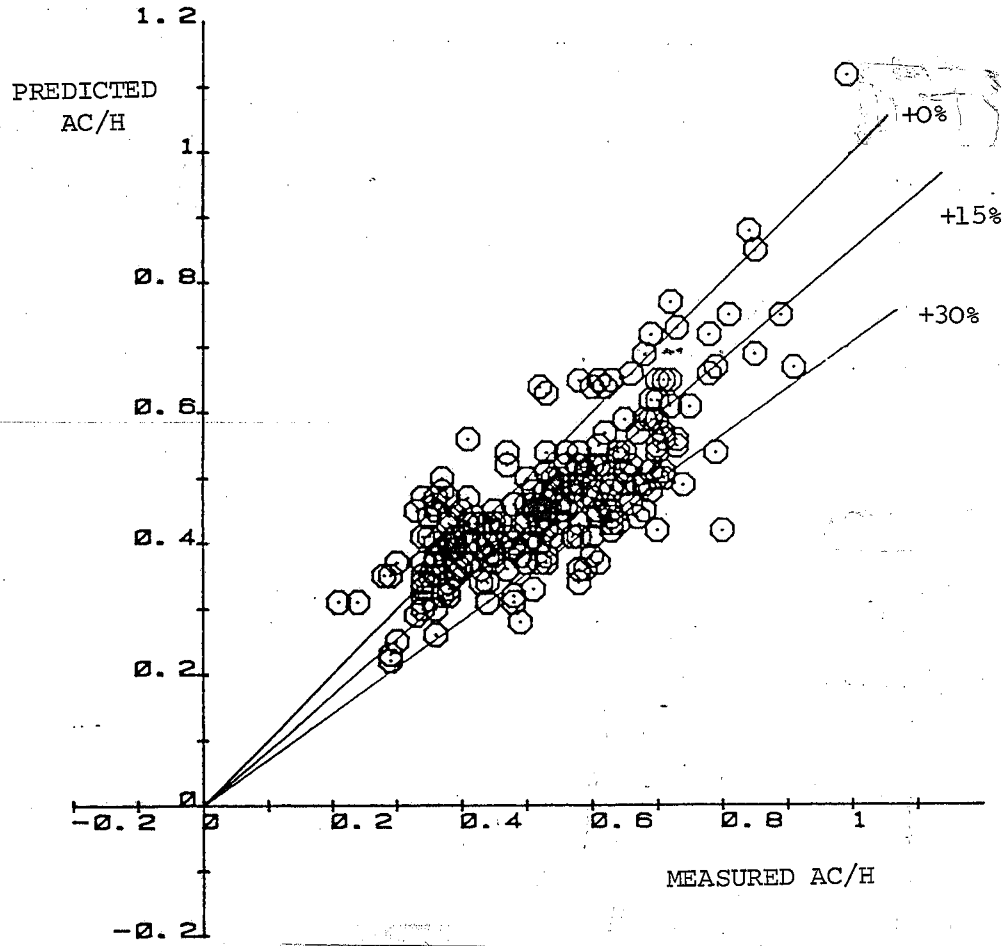



Figure A9.1.7 Comparison of measured and predicted infiltration rates

## Appendix 9.2

## Use of the British Gas Formula for occupied houses

The British Gas equation predicts infiltration rates to an accuracy of about ± 20%. This equation alone would not be sufficient to estimate real ventilation rates in the occupied houses, as they have different leakage characteristics (see Table 9.1) and occupants are at liberty to open windows and external doors when they choose, thus increasing the level of ventilation considerably.

However, a knowledge of the leakage characteristics has been obtained from the pressure tests, and hourly data exists for the occurrence of window openings. Furthermore, British Gas carried out some ventilation rate measurements in the test house with windows open, and a crude characterisation obtained. Thus it is possible to make an attempt at estimating the ventilation rates in the occupied houses. This has been done for four houses (the only houses with window opening data), in order to compare the likely levels of infiltration, and to estimate the relative effects of window-opening.

### A9.2.1 Corrections for leakage differences

It is widely assumed that there is no universal simple relationship between leakage and infiltration rate. One would expect the infiltration rate to increase with leakage area for a given weather condition, but when different houses are compared, the distribution of the cracks around the respective houses may be different and this may cause non-linear differences in infiltration rates.

However, measurements in 12 U.K. houses of different leakage areas carried out by the BRE (reference 9.1) suggest that a linear relationship can reasonably be assumed. Figure A9.2.1 shows their results in terms of the whole house infiltration rate at 3.5 m/s wind speed plotted against the air leakage at 50Pa pressure difference. These results show that for their sample, a doubling of air leakage approximately results in a doubling of infiltration rate.

This simple assumption has been applied to the Linford houses. Some justification for this can be claimed, considering that the houses are of identical design, and were built at approximately the same time to the same specification by the same team of workmen.

Using the test house as a reference, the infiltration rates have been assumed to be different to those in the test house, under identical internal and external conditions, by a factor $\frac{Q_o}{Q_t}$ where $Q_o$ and $Q_t$ are the air leakage at 50Pa in the occupied houses and the test house respectively. Thus the infiltration rate in an occupied house, Rho, is given by:

$$Rho = \frac{Q_o}{Q_t} \cdot R_h$$ where $R_h$ = infiltration rate in test house, given by British Gas prediction formula

Using the values for $Q_o$ and $Q_t$ from Table 9.1, the multiplying factors $(\frac{Q_o}{Q_t})$ are:

| | |
|---|---|
| House 35 | 0.72 |
| House 36 | 0.96 |
| House 38 | 0.92 |

It was discovered that the pressure test for house 33 had been carried out incorrectly, invalidating the result. Rather than excluding this house from the analysis (and subsequent energy balance analysis), a value of 0.1 $m^2$ effective orifice area at 50Pa was assumed (see Table 9.1), making the corresponding multiplication factor for this house 0.92.

### A9.2.2 The effect of window openings

It is extremely difficult to derive accurate ventilation rate prediction equations for window opening, because of the infinite number of possible combinations of window openings (size and position). Furthermore, the effect of a given configuration of window openings will depend on weather conditions. However, some simplifying assumptions can be made.

An obvious assumption is that the position of the window openings does not matter, so the whole house ventilation rate depends only on the number and size of the openings. Taking this a step further, it can be assumed that the ventilation rate is simply proportional to the total open area of the house. This leads to the following expression for the ventilation rate with windows open:

$$R_{hw} = (1 + \frac{Aw}{Ae})$$

where Aw is the total open area of windows, $R_h$ is the infiltration rate (windows closed) for the given weather conditions (thus the effect of weather is assumed to be the same for windows open as it is for windows closed), and Ae is the effective orifice area of the house, found from pressure tests (Table 9.1).

Some measurements of the whole-house ventilation rate with some windows open were carried out in the test house by British Gas in November 1981. A range of open-window areas (Aw) was covered, increasing the effective orifice area of the house by a factor ranging from 1.4 to 4.5 (the effective orifice area with windows shut is approximately 0.1 $m^2$).

The above expression for $R_{hw}$ was tested by plotting measured values of $R_{hw}$

against the calculated values ($R_h$ being calculated from the British Gas formula for infiltration rate). This is shown in Figure A9.2.2. Perhaps surprisingly, the agreement is fairly good; the mean ratio of prediction to measurement is 0.985, with a standard deviation of 0.310.

One feature illustrated by Figure A9.2.2 is that the level of agreement seems to depend on the basic weather condition - for low wind/high stack, the prediction equation overestimates, whereas for high wind/low stack, it underestimates.

This expression was used to allow for window openings in the occupied houses. One difficulty, however, is in assuming the size of the window openings, as the recorded data consists of simply the status of the window i.e. whether it is open or shut. This is obviously a problem, and potentially a large source of error in the estimate of ventilation rates during periods when windows are open. An "average" window opening was chosen as 10 cm, i.e. the glass panes were drawn back a distance of 10 cm. The open-window area, Aw, is then equal to the height of the window frame x 10 cm. As there are four different sizes of window frames, each window opening was weighted according to its height.

Thus the full expression for the estimated ventilation rates in the occupied houses is:

$$R_o = \frac{Q_o}{Q_t} \times R_h\left(1 + \frac{Aw}{Ae}\right)$$

where $R_o$ = estimated ventilation rate in occupied house

$R_t$ = infiltration rate in test house under same weather conditions

$Q_o$ = Air change rate at 50Pa in occupied house

$Q_t$ = Air change rate at 50Pa in test house

Aw = effective window opening area

Ae = effective orifice area (at 50Pa) of occupied house

($R_h$ is calculated from the prediction equation described in Appendix 9.1).

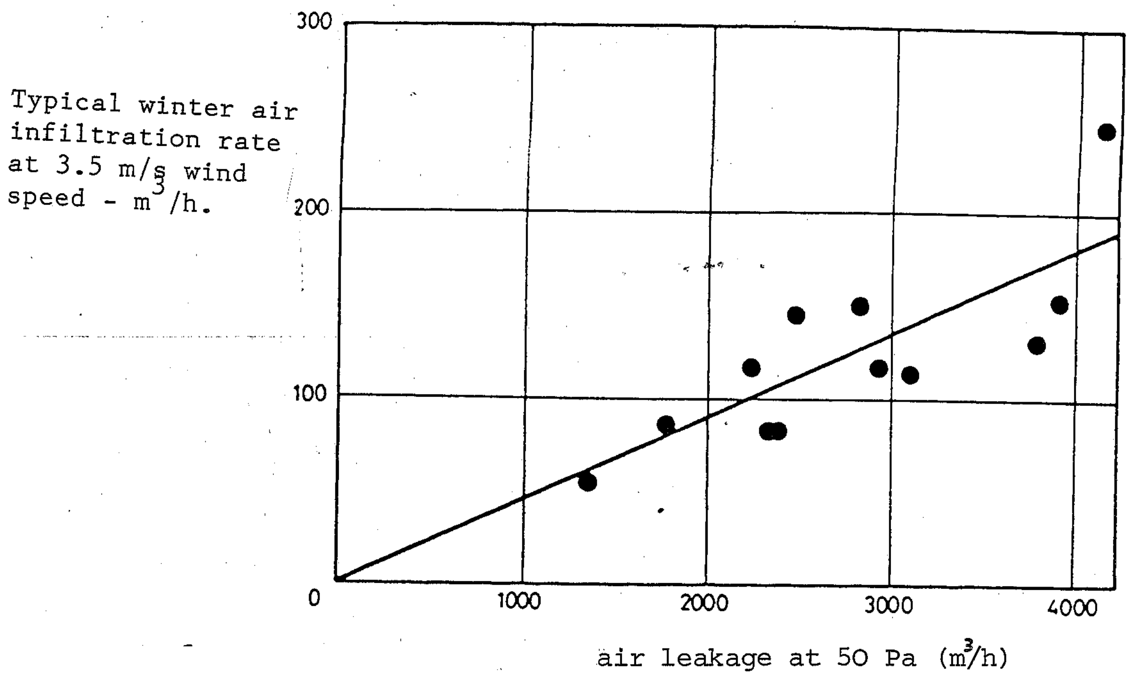



Figure A9.2.1 Variation of whole house infiltration rates with air leakage from BRE sample (reference 9.1)

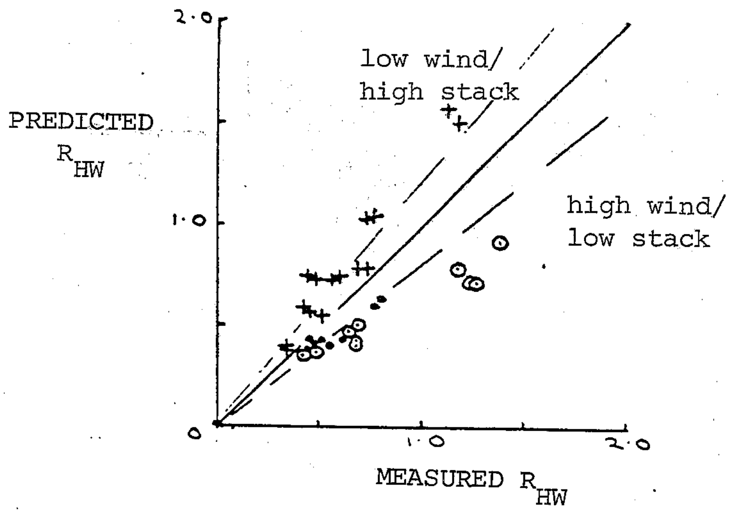



Figure A9.2.2 British Gas ventilation rate measurements with windows open (ref. 9.4)

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9.2 3rd Air Infiltration Conference, 1982. Air Infiltration Centre, Bracknell.

9.3 R.Socolow, Saving Energy in the Home (Twin Rivers), Princeton,1982.

9.4 Ventilation Measurements in an O.U. Test House, D.W.Etheridge & J.P.Smart, British Gas, December 1982.

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# 10. SOLAR GAINS

CONTENTS



This large and extensive chapter deals in detail with the passive solar performance of the houses in both qualitative and quantitative terms. Aspects covered include: winter absorption of solar energy, summer overheating and the use of thermal mass, the effect of "window clutter" on performance, the experimental determination of house "solar apertures", and the calculation of absolute and marginal solar gains.

# 10. SOLAR GAINS

## 10.1. Introduction

The Linford houses have been designed to maximise passive solar gains. They face south, are not overshaded by other buildings and have the main rooms and glazing concentrated on the south side.

This chapter deals with the qualitative and quantitative assessment of these solar gains.

Section 10.2 deals with the winter absorption of solar energy, how it displaces space heating and is stored in the fabric of the house until evening.

Section 10.3 deals with summer overheating from a theoretical point of view, and the implications for correct orientation and the use of thermal mass.

Section 10.4 describes the observed window clutter, net curtains, half drawn blinds, etc., which impede the absorption of solar energy.

Section 10.5 deals with the experimental determination of the test house solar aperture by the use of thermal calibration experiments. The results are compared with similar calculations for the occupied houses and their observed level of window clutter.

The final section looks in detail at the calculation of solar gains, both in absolute terms and more important in marginal terms, i.e. how much less space heating energy the Linford houses have used than the equivalent 'non-solar' house at the same insulation level.

In general the experiments and analysis are fairly new and do not appear to have been used in previous passive solar work. The main attention has been given to assessing passive solar gains used in displacing space heating (and therefore saving money) rather than in maintaining specific temperatures or 'increased comfort'.

The thermal calibration work forms part of a separate project on the rapid thermal assessment of houses, funded by the Science and Engineering Research Council. This work will form a separate later report and will incorporate the more mathematically dense aspects of the Linford test house thermal calibration.

## 10.2. Absorption of Solar Radiation

The basic design concept of a direct gain passive solar house is that of a highly insulated shell with thermally massive internal walls and a large area of south-facing glazing (see Figure 10.1). Solar gains during the day are absorbed in the thermal mass and stored through to the evening, displacing auxiliary space heating.

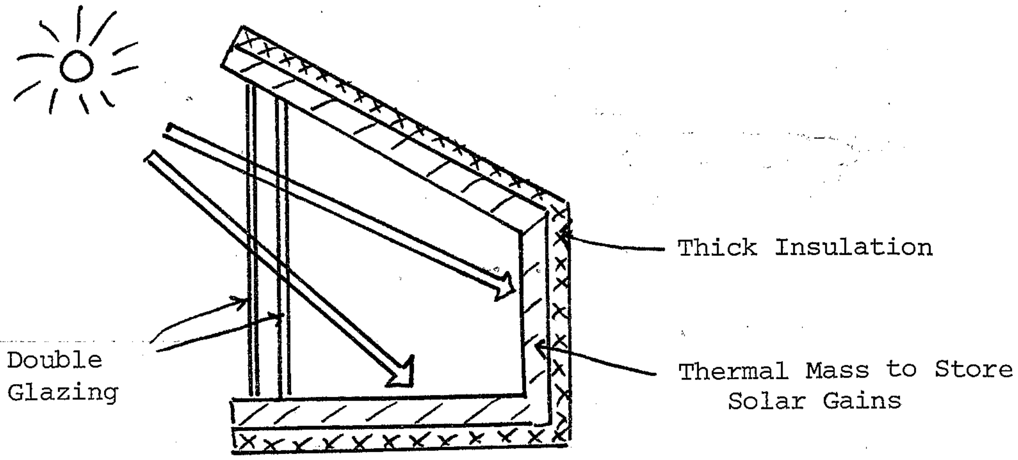



Figure 10.1 Notional Direct Gain Passive Solar House

10.2.1. The Daily Cycle

The process by which solar energy is absorbed and stored has several steps. For clarity it is simplest to start with conditions in the test house. Here there were no free heat gains from cooking, etc., and the internal temperature was kept as far as possible constant by the use of electronically controlled fan heaters. The occupied houses have the added complexity of intermittent heating, free heat gains and boiler cycling.

The solar absorption in the test house is illustrated in Figures 10.2 and 10.3. These diagrams show internal and external temperatures, solar radiation, wall and floor heat fluxes and electric heating for three days in March 1982, a dull day followed by two sunny ones.

The daily pattern of events on a sunny day is roughly as follows:-

1. The sun rises.

2. The external air temperature begins to rise rapidly.

3. Solar radiation enters the windows, striking the floor.

4. A small proportion of this radiation penetrates the carpet and is absorbed in the floor beneath.

5. The remainder of the radiation is dispersed in the air inside the house.

6. This energy, together with the rapid reduction window and ventilation losses due to the rising external temperature leads to a slight rise in internal temperature.

7. This rise in temperature affects the thermostat(s) allowing solar gains to displace space heating immediately.

8. Once the space heating has been totally displaced the internal temperature rises more rapidly.

9. This rise in internal temperature causes a rapid flow of energy into storage in the walls.

10. Towards sunset the solar radiation drops off and the external temperature begins to fall, increasing 'massless' heat losses such as the windows, ventilation loss and to a certain extent, the roof.

11. The internal temperature falls slowly back to the thermostat setting. During this period the space heating is supplied from stored solar energy flowing back out from the walls.

12. Once the thermostat setting is reached the space heating comes on again, but relatively slowly.

13. Although the 'massless' heat losses increase in the evening with the falling external temperature, the heat loss through the thermally massive walls lags about 8 hours behind the daily swing in air temperature, reaching a minimum in the evening.

14. Throughout the evening, although the internal air temperature is constant, heat still flows out of the walls, displacing space heating energy as the deeper wall layers return to equilibrium. This state continues until dawn when the cycle repeats.

On dull days the solar radiation may not be enough to totally displace the space heating and the cycle skips stages 8-12.

The cycle is further complicated by the fact that the solar gains are not evenly distributed over the house, each room responding to the solar input to a greater or lesser extent.

We can now look in more detail at the various steps.

### 10.2.2. Floor absorption

The absorption of solar radiation in the floor has been studied using the two heat flux sensors set into the concrete floor slab. These were positioned approximately 0.6 m and 2 m from the south-facing living room windows (see Chapter 8 for the precise positions).

Although Figure 10.3 indicates that the floor sensors have very high heat fluxes during the day, only a small proportion of the incident solar radiation actually penetrates the floor surface into the concrete. This has been investigated for three conditions of the floor surface:

1. Bare - plastic tile surface (this is the condition in Figure 10.3).

2. With carpet tiles.

3. Insulated over with 50 mm polystyrene insulation.

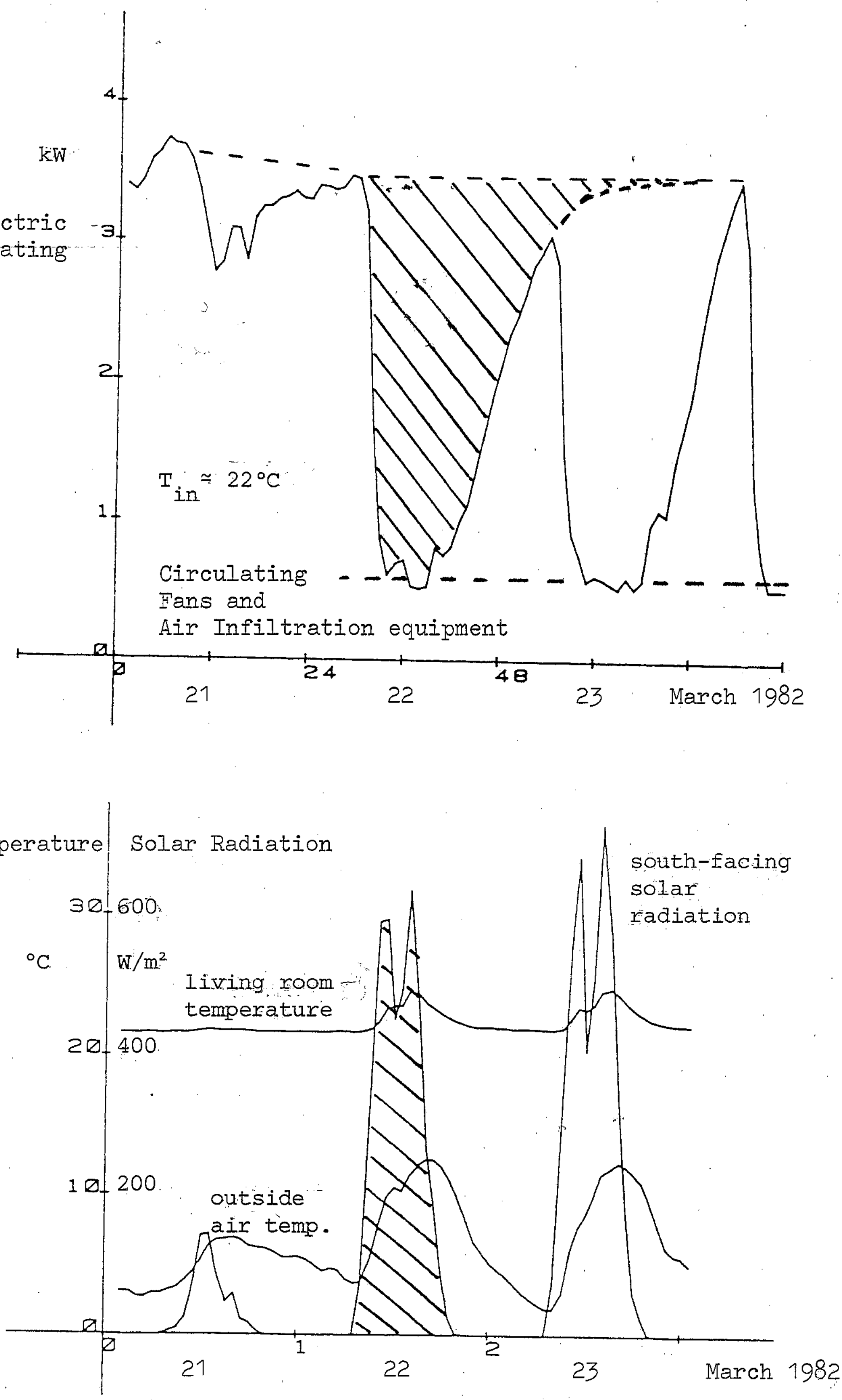



Figure 10.2 Test House – Effect of Solar Gain on Space Heating

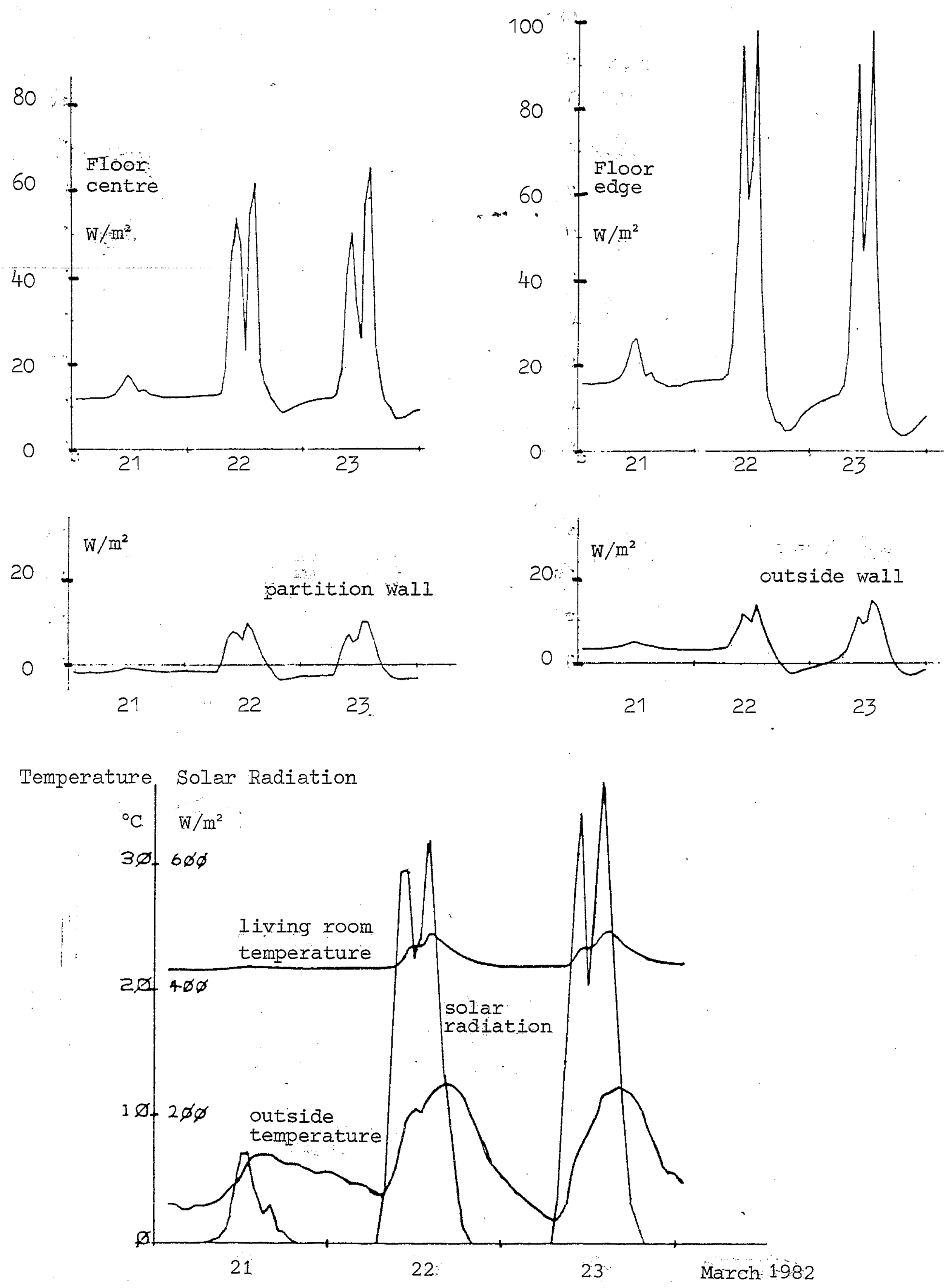



Figure 10.3 Relative Magnitudes of Floor and Wall Surface Heat Fluxes 21st - 23rd March 1982.

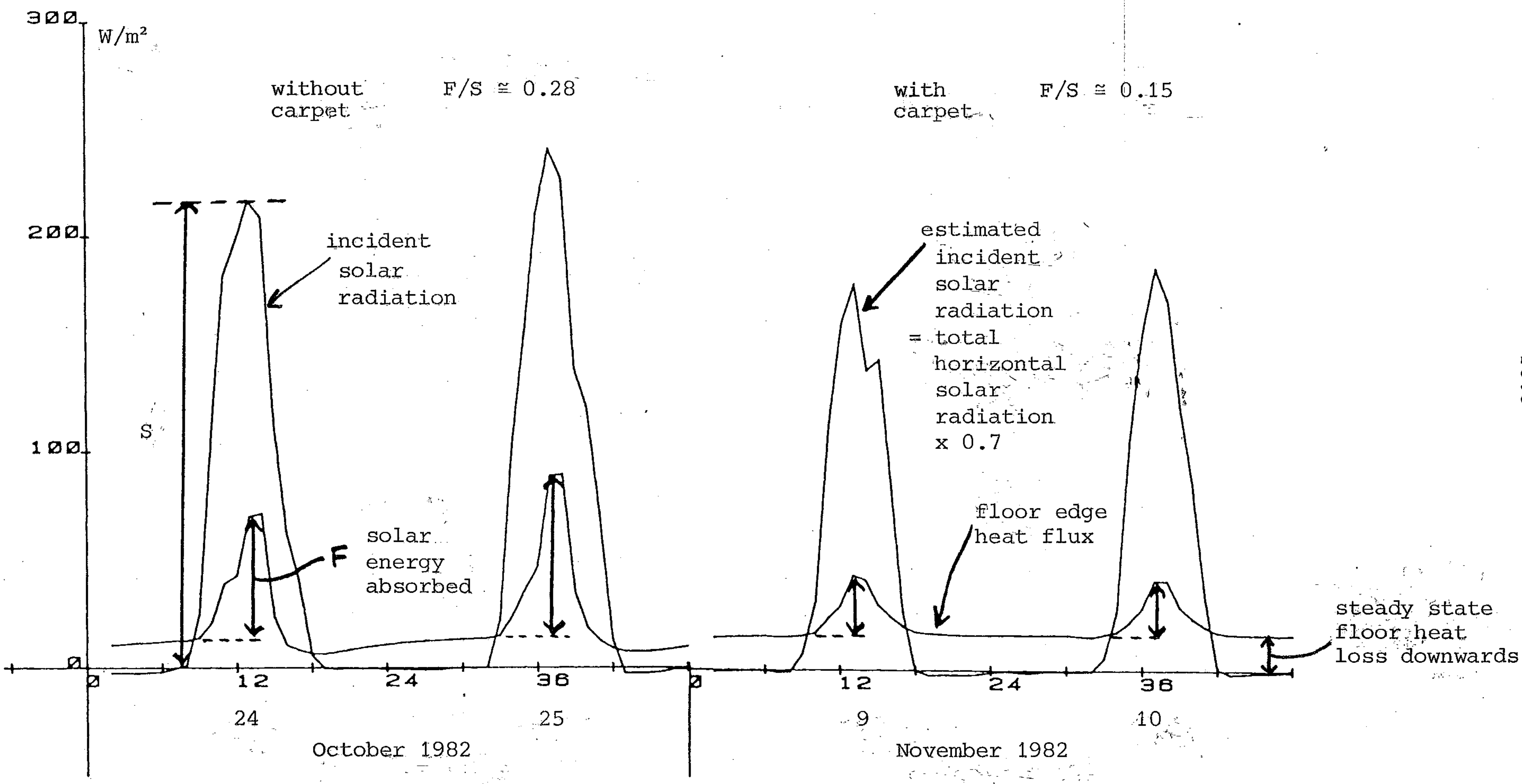



Figure 10.4 Effects of Carpet on Floor Heat Flux

Figure 10.4 shows plots of floor heat flux measured at the sensor closest to the window and incident solar radiation, estimated as 70% of the measured total horizontal solar radiation. For a bare floor, only 28% of the incident radiation appears to enter storage. This poor performance may be due to the presence of a small air gap between the plastic tiles and the concrete slab beneath. Carpet tiles, which were actually quite thin, reduced the solar absorption to 15%. Finally, totally insulating over the surface with 50 mm polystyrene reduced it to an almost undetectable 2%.

It would seem, therefore, that for practical purposes in houses and offices with thick carpets, the solar absorption in the floor is likely to be about 10%. The concrete floor slab cannot thus be considered seriously as 'primary thermal mass' from a solar point of view.

### 10.2.3. Wall absorption

This has been studied with the aid of two heat flux sensors, one set in the inside surface of the end living room external wall, and the other set in the surface of the living room partition wall facing the windows.

In this case the absorption of solar energy is driven more by the rise in room temperature rather than the direct rays of the sun. In passive solar terminology it is said to be 'secondary' thermal mass.

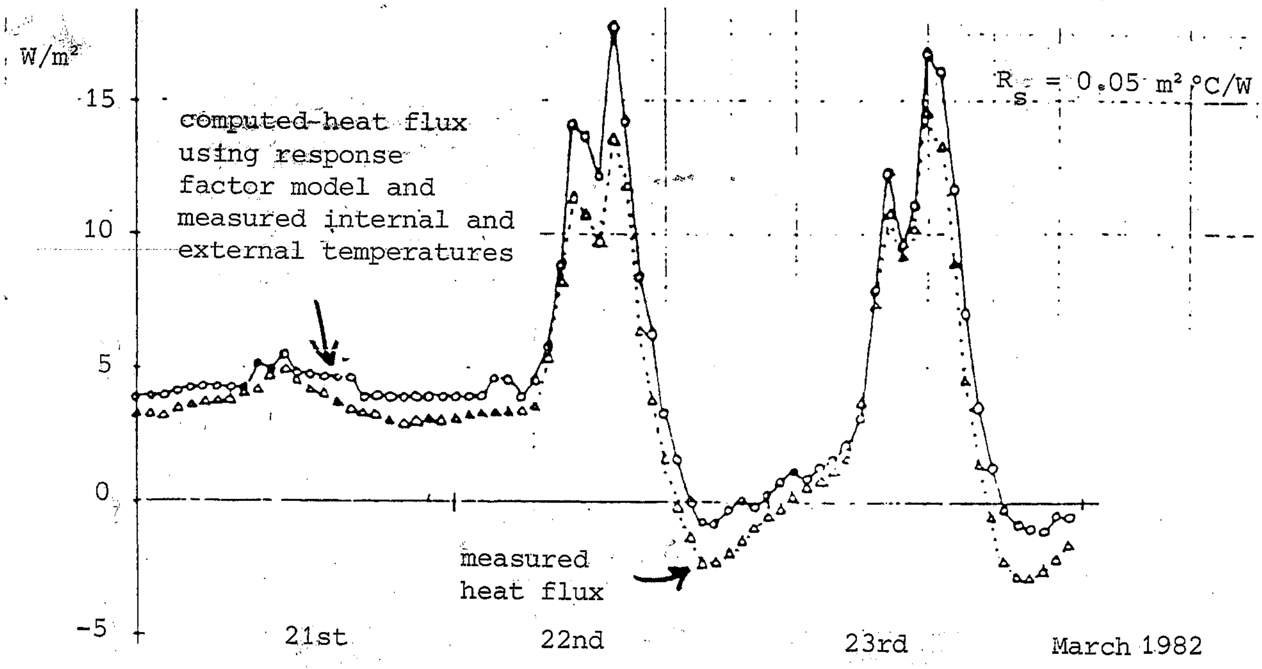
Although the magnitude of the response shown in Figure 10.3 is small in terms of $W/m^2$, it is likely that this response is evenly spread over 30 $m^2$ of living room interior wall surface. Thus the surge of energy flowing into the walls on each of the two sunny days would put about 2 kWh of solar energy into storage in the living room walls alone.

The response of the wall surface sensors corresponded very closely with calculated heat flows using a response factor model with measured internal and external temperatures (see Figure 10.5). The fit of the model is very dependent on the choice of inside surface air thermal resistance, and the value of $R_S$ = 0.05 $m^2\,°C/W$ was chosen to reflect the high level of air movement in the test house produced by the circulating fans necessary for the air infiltration measurements. The slight negative offset of the measured trace may either be a monitoring fault or a problem due to the difference between the measured air temperature and the radiation temperature experienced by the wall surface due to the proximity of the cold window surface (see also Section 8.2).

This good fit of measurements and theory does inspire a certain confidence in the NBSLD model, though a program error in the published version was discovered at this point which did affect the response of highly insulated thermally massive walls (see Appendix 10.1).

### 10.2.4. Displacement of space heating - test house

The displacement of auxiliary heating by solar radiation and the effect on various room temperatures is possibly a little confusing at first. It is simplest to first describe measured results in the test house, followed by a computer simulation of effects in an occupied house, finally looking at measured occupied house data.



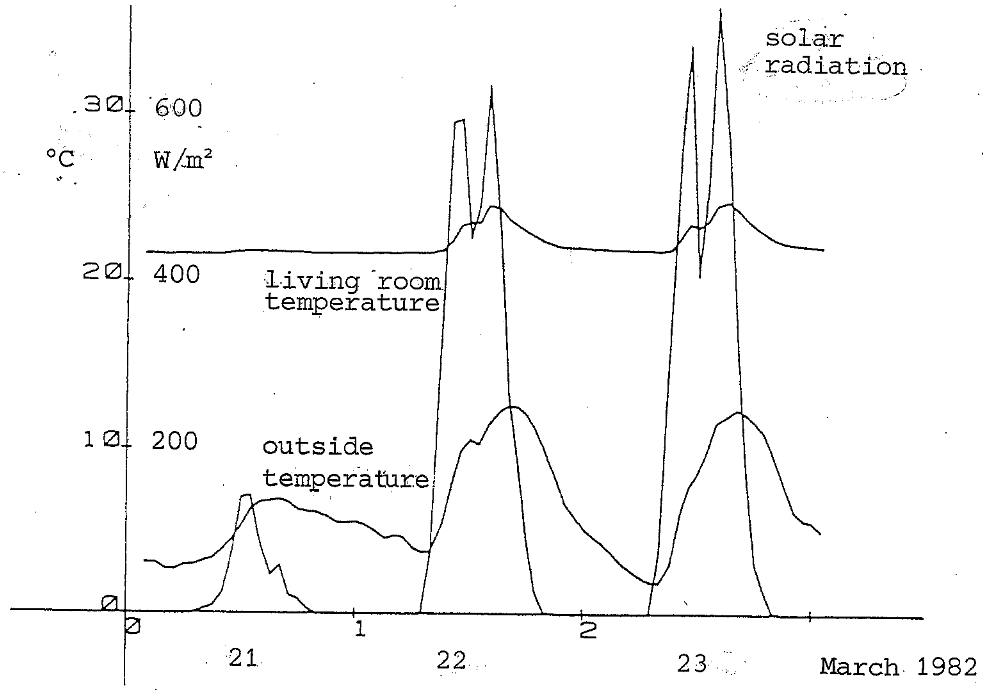




Figure 10.5 Wall Surface Heat Flux

The displacement of space heating can be seen as a two stage process. As shown in Figure 10.2, on a dull day the solar radiation simply immediately replaces some of the auxiliary space heating energy. There is almost no increase in internal air temperature and as a result almost no storage of solar energy in the walls, although a small amount does enter the floor (see Figure 10.3). The lack of a rise in temperature means that there is no increase in house heat losses and as a result the solar gains can be thought of as 100% useful.

On sunnier days some of the solar input first displaces all the space heating (the residual electricity consumption in Figure 10.2 is that of the ventilation rate monitoring equipment and the fans circulating air around the house - all extra heat input). Once this has happened, then the internal air temperature begins to rise, forcing energy into storage in the walls, in addition to the energy put into storage in the floor by the direct rays of the sun. The rise in internal temperature means that the house heat loss is slightly increased and thus a small amount of the solar energy is possibly 'wasted', though this depends on whether this extra temperature can in any way be considered as 'useful'. Either way, the proportion of energy put into storage is likely to be very high, as will become apparent from the computer simulation.

In the evening, the internal temperature falls as the solar input is removed. For a while the house is totally heated by the solar gains re-emerging from the walls and floor. When the internal temperature reaches the thermostat setting, the heating comes on again, but only slowly. Although the internal air temperature is now almost constant, solar energy still flows out of the walls and floor as deeper layers return to equilibrium. Response factor theory suggests that this process will take the form of a very long exponential decay lasting well into the next day and beyond.

### 10.2.5. Distribution of solar gains - test house

In the test house experiments it has been possible to look at the distribution of solar gains throughout the house by monitoring the separate outputs of four of the five electric fan heaters used. Each of the heaters had its own separate electronic thermostat. Two heaters were positioned at opposite ends of the living room/dining room, one in the kitchen and two upstairs on the landing, facing into and controlled by thermostats positioned in two of the south-facing bedrooms.

Figure 10.6 shows the recorded power outputs for a typical dull day. This shows that the solar radiation simply displaces space heating fairly evenly over the south side of the house, but almost none is displaced in the kitchen. This is a little surprising in view of the fairly energetic circulating fans attempting to mix the air throughout the house.

Figure 10.7 shows a similar plot for a sunny day. This clearly shows the immediate total displacement of space heating and the storage of the solar gains far into the evening. In the south-facing rooms the space heating has been displaced by 8.30 a.m., only 2½ hours after dawn, with the kitchen lagging about an hour behind. The kitchen is the first room to require heating again in the evening, the south-facing rooms not requiring any heating until sunset. The heating comes on slowly in all rooms and even by midnight it is apparent that solar gains are still emerging and a steady state has not yet been reached.

8

## Comparison of Room Heating Requirements

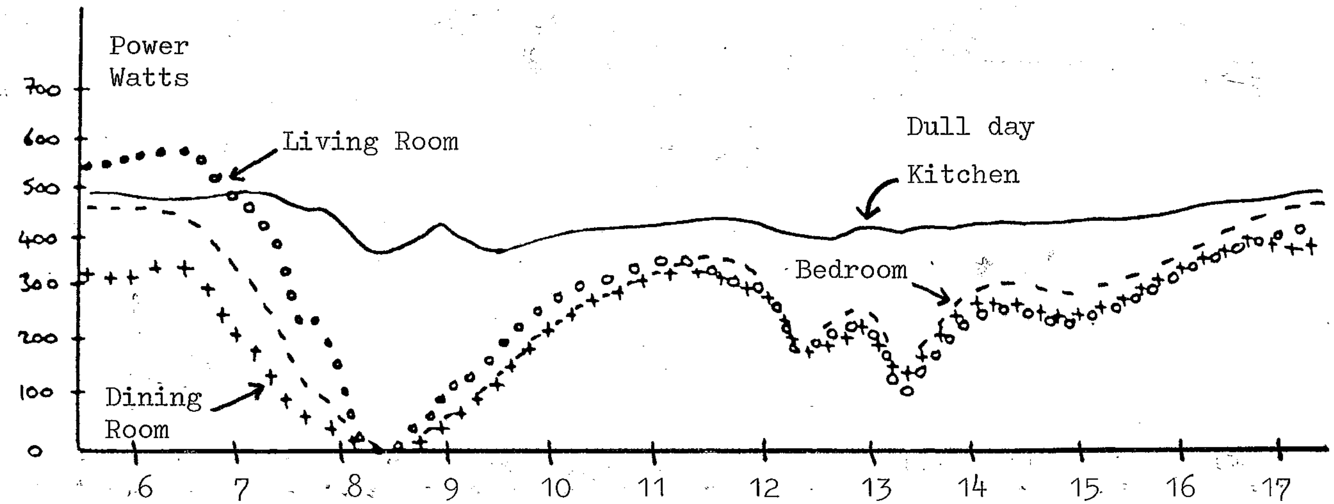



Figure 10.6 Heater Power Traces, 1st March 1982 DULL DAY

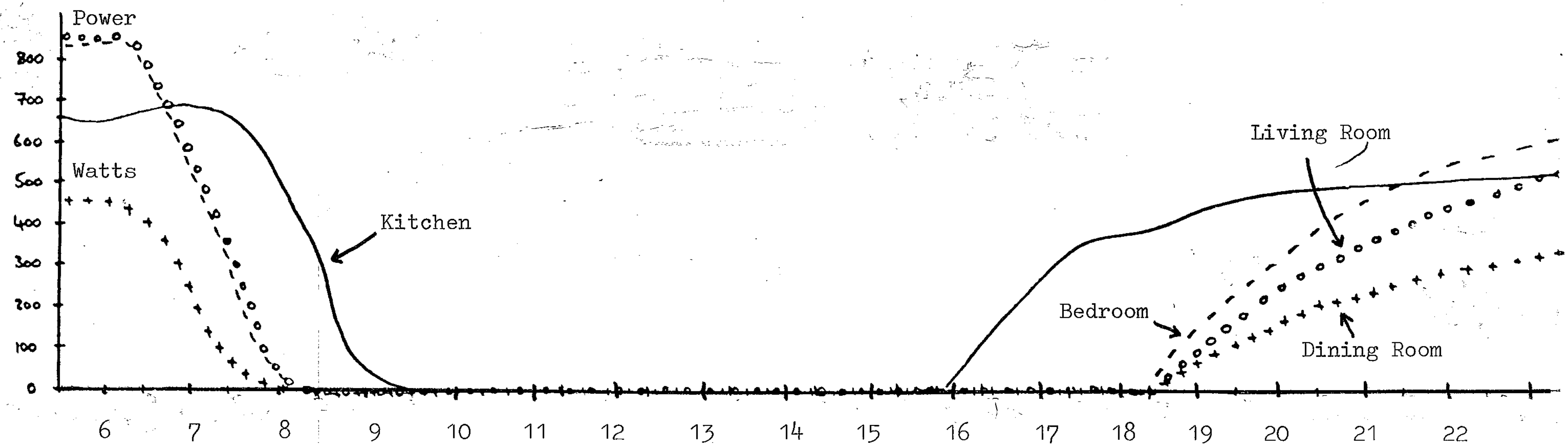



Figure 10.7 Heating Power Traces, 5th March 1982, CLEAR SKY SUNNY DAY

Figure 10.8 shows the corresponding room temperatures during this day. These are from wall-mounted temperature sensors and may differ slightly from the temperatures recorded by the sensors controlling the heaters. This figure clearly shows the temperature rises in the south-facing rooms, the bedroom temperature reaching 26°C in the early afternoon. In the kitchen, the sluggish response of the heater is matched by a very small rise in temperature. The apparent lack of penetration of solar gains into the kitchen is probably a good thing given the high level of free heat gains that are likely to occur there, especially in the early evening. This, and the implications for the positioning of central heating thermostats, is discussed later.

The general technique of measuring energy inputs by displacement appears to be potentially very useful. In setting up the heaters it was found that adjusting the thermostat on one brought an almost immediate response from the others. Turning on a light would bring an immediate compensating response from the room heater. It would seem that this method could be used to measure all kinds of free heat gains, boiler casing losses, etc.

10.2.6. Predicted displacement of space heating - occupied house simulation.

In the occupied houses matters are somewhat more complicated. The use of intermittent heating and the presence of large free heat gains from cooking, lights, etc., tends to make the effects of the solar gains a little difficult to see, especially regarding the storage into the evening. These effects can be seen more easily in a simulation.

Two NBSLD runs have been made for two days in January 1969, one with solar gains included, the other without. The weather consists of a sunny day followed by (an preceded by) a dull one. Free heat gains have been included in each run.

Figure 10.9 shows plots of internal and external temperatures, calculated solar gains into the house and space heating demands with and without solar gains included. Also plotted is the difference hour by hour between the two sets of space heating demands, this being the heating energy saved by the solar gains.

The plots show the heating coming on fairly substantially first thing in the morning to bring the house up to the thermostat setting. Without the solar gains, the heating falls away slowly during the day, especially in the evening when the free heat gains rise to a peak. With the solar gains included, the space heating is completely displaced by solar radiation from soon after dawn to sunset. There is a small temperature rise in the house as the solar radiation not used to displace space heating is put into storage in the walls.

In the evening, both the space heating curves, with and without solar gains look rather confused. The difference between them, though, the solar energy savings, shows the same general shape as that measured in the test house. There is a rapid flow of solar energy from storage after sunset as the internal temperature falls tailing away exponentially in the evening but lasting through to the next day. The smooth exponential tail is somewhat limited by the quantisation of the plotting process used for Figure 10.9.

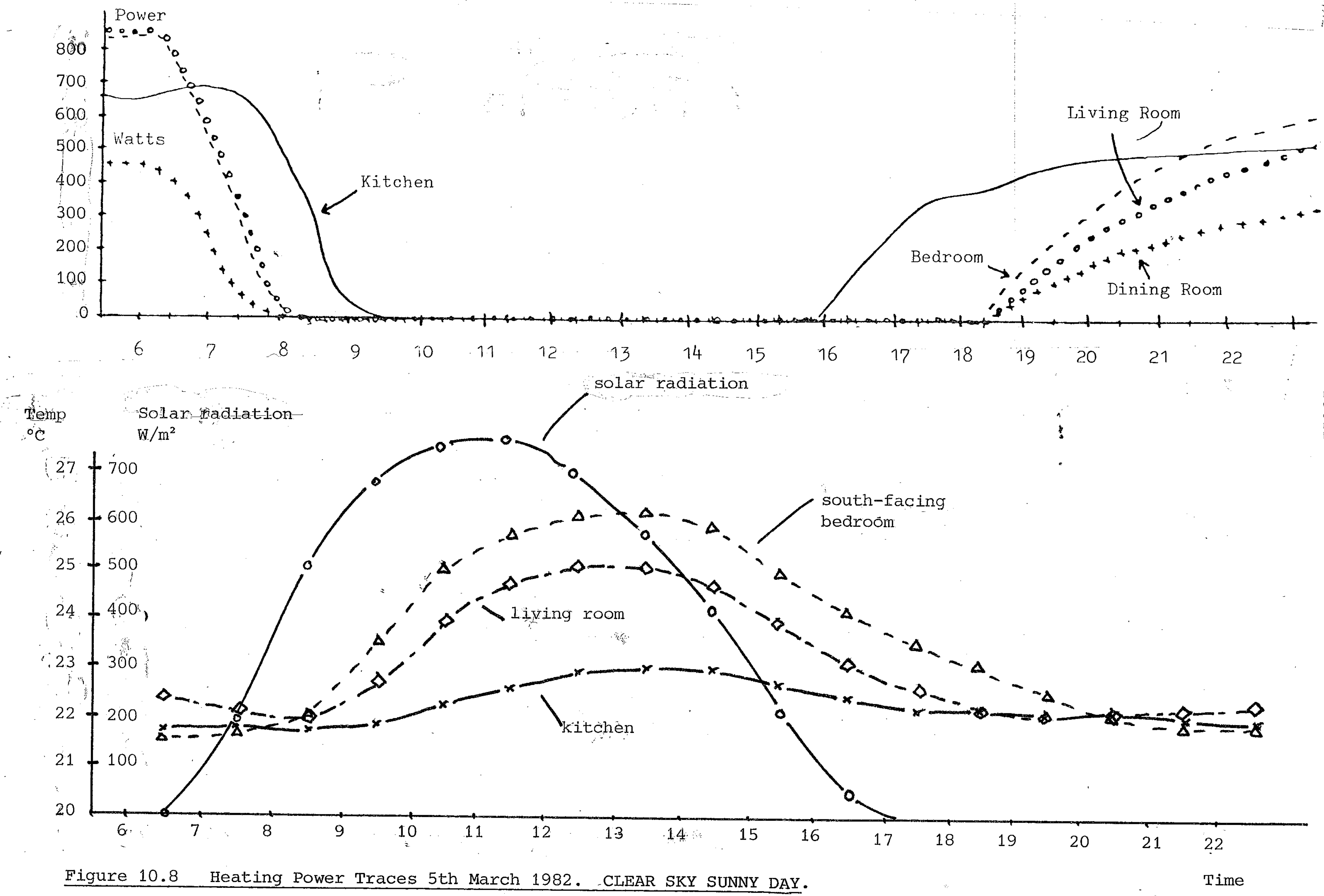



Figure 10.8 Heating Power Traces 5th March 1982. CLEAR SKY SUNNY DAY.

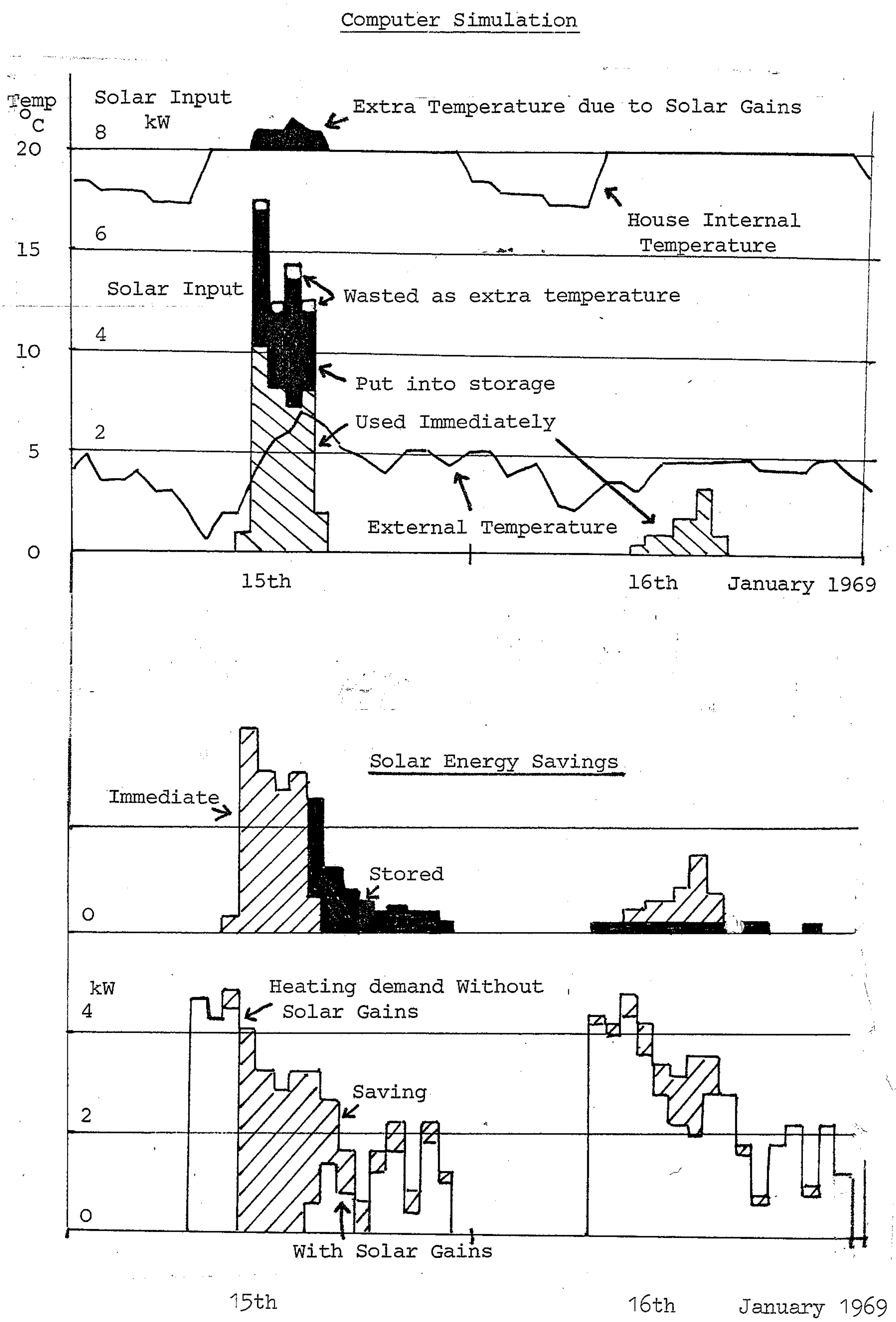



Figure 10.9 Effects of Solar Radiation on Occupied House Heating Demand

In this relatively crude simulation (the house is only treated as a one-room box), it is easy to break down the solar input into three parts, that used immediately to displace space heating, that 'wasted' on extra daytime temperature and the remainder that is put into storage. For the sunny day about a half of the solar input is used immediately and most of the remainder is put into storage. The amount lost as the midday increase in internal temperature is a very small proportion of the total.

The ratio of energy put into storage to that lost as a temperature increase can be calculated from response factor theory. The method is rather stylised but suggests that less than 10% of the stored solar energy is likely to be lost in this way (see Appendix 10.2).

10.2.7. Measured displacement of space heating - occupied houses.

Figure 10.10 shows plots of space heating, solar radiation and internal and external air temperatures for one of the occupied houses for two typical January days, one dull, one sunny.

The general pattern is the same as the simulation, though the weather is somewhat colder. There is a peak of space heating in the early morning bringing the house up to the thermostat setting, followed by a slow decrease in heating throughout the dull day. On the sunny day, the space heating has been totally displaced by solar gains by midday. The internal temperature then rises, especially in the living room. Towards sunset, the living room temperature falls back to the thermostat setting and the heating comes on again, though at a slightly lower level than for the preceding dull day, despite a colder air temperature.

Obviously real house conditions are more complicated than either the simulation or the test house experiments. The heating system does not control each room temperature perfectly and the free heat gains and boiler cycling in the evening make it difficult to detect stored solar energy.

Figure 10.11 shows completely different conditions towards the end of the heating season, in late March. Here solar gains almost totally heat the house, auxiliary space heating being reduced to a small amount late in the evening. The heating system appears to be under manual control, rather than on the time clock, allowing the solar gains to perform the morning warm-up function. This may be a good reason for facing passive solar houses slightly east of south.

In this case, although there are large temperature swings in the bedroom, the living room is kept fairly close to 21°C, the probable thermostat setting. Measurements of window openings during this period indicate that the living room windows were open during most of the sunny days, thereby rejecting some of the solar gains, but closed in the evening and night.

Figure 10.12 shows a completely different response to solar gains for the same period. Here, in a normally fairly low temperature house, solar gains have been allowed to charge up the living room temperature to well above the normal 18°C. It is likely that the house is unoccupied during the midday period and the living room windows appear to have been kept shut.

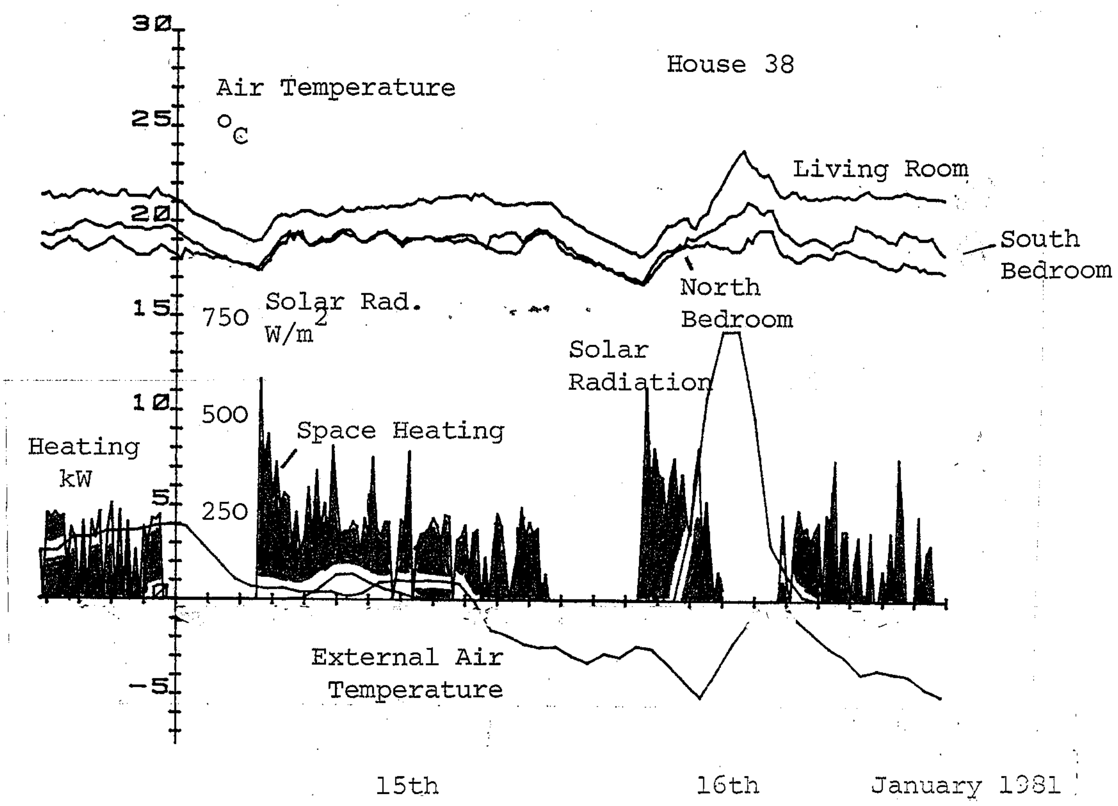



Figure 10.10 Solar Radiation and Space Heating

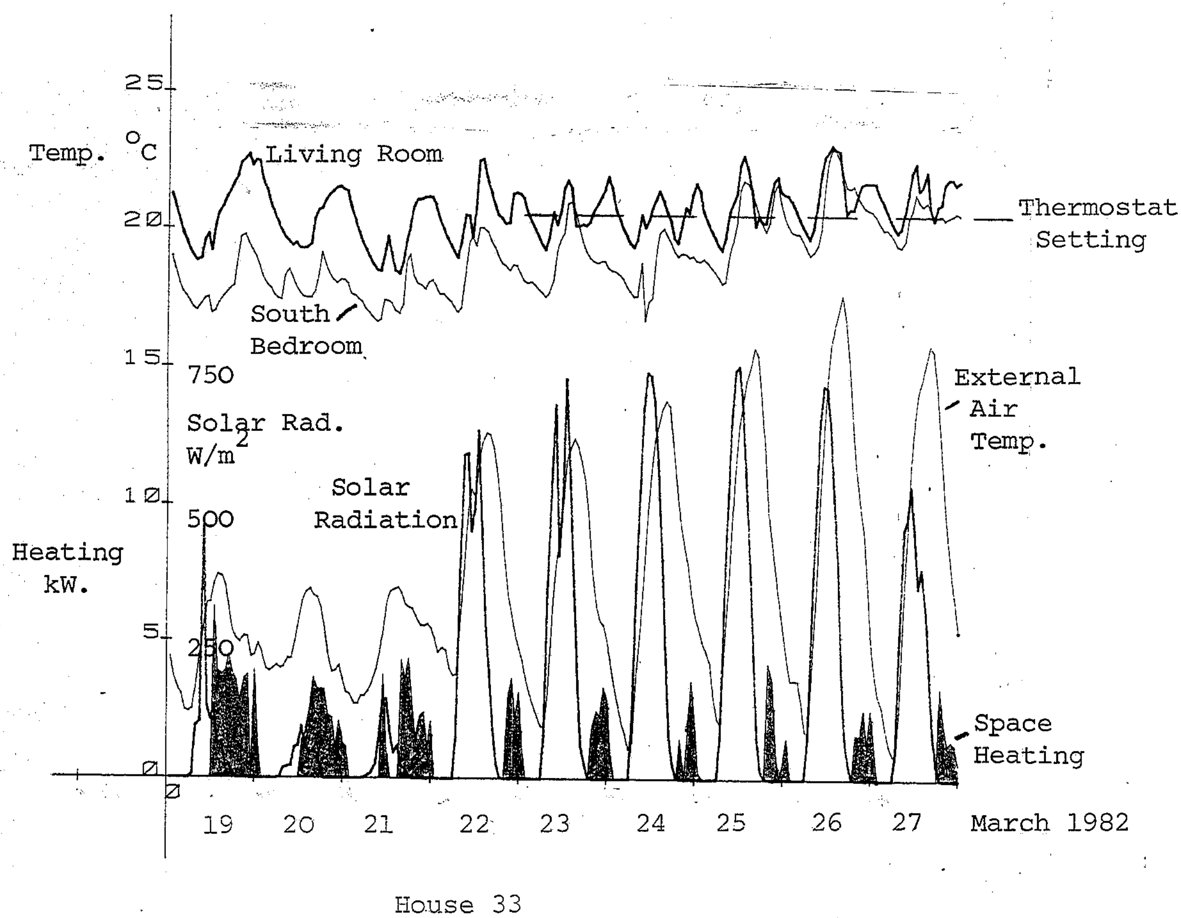



Figure 10.11 Solar Radiation and Space Heating

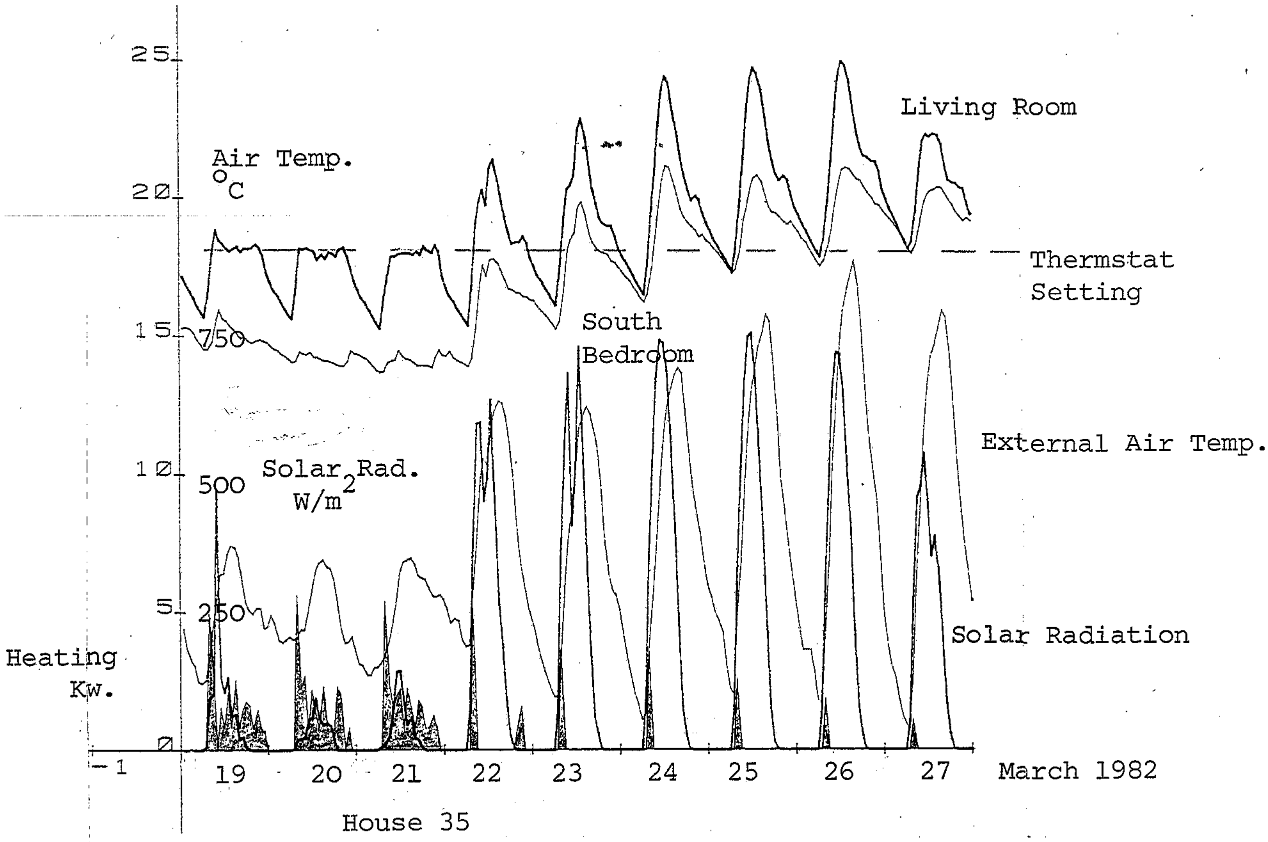



Figure 10.12 Solar Radiation and Space Heating

By the early evening, the living room temperature has fallen to around 21°C, but the stored solar energy is sufficient to totally supplant all the space heating for the whole evening.

There is obviously much scope for research in actively controlling the house heating system to make the best use of solar and free heat gains, rather than simply relying on the time clock and thermostat.

### 10.2.8. Solar gains, thermostat positions and thermal mass.

In order to make good use of the solar gains, it is obviously necessary to have a heating system that is responsive to them. It would not, for instance be much use positioning the main central heating thermostat in the hall, given the poor penetration of solar gains to the north side of the house. This would simply leave the heating full on during a sunny day, causing considerable overheating.

The main thermostat in the Linford houses is on the rear wall of the living room, which gives quite an adequate response to solar gains. Regression analysis of room temperatures with outside temperature and solar radiation has shown that while south-facing rooms, not surprisingly, tend to be warmer on sunny days, the kitchen tends to be cooler. This is because the auxiliary heating is cut off to it and little solar energy replaces it.

While this is probably not a serious problem, it would perhaps suggest that for a proper passive solar house design, the heating system should be organised on a north/south basis rather than an upstairs-downstairs one.

Also, given the lack of response of the northerly rooms to solar inputs there seems little point in giving them extra thermal mass, especially if this increases construction cost. Although the kitchen may generate quite high levels of free heat gains, the peak levels (approximately 1.5 kW) are still less than peak solar gains of around 6 kW that occur in the living/dining room and may be sustained for several hours.

## 10.3. Summer Overheating

At the design stage considerable concern was felt over the problems of possible summer overheating. Early modelling showed that the benefits of insulating a house to stop heat escaping in the winter created a summer problem of encouraging it to escape.

Five methods of avoiding summer overheating were contemplated:-

1. Shading roof eaves and a balcony.
2. Reflective window blinds.
3. A high ventilation rate.
4. Correct orientation.
5. Thermal mass.

The balcony and overshading roof eaves were rejected because of the high cost and possible loss of useful solar gains in the spring (see Chapter 2).

Reflective window blinds also were rejected because of cost, but the cheaper paper blinds installed were likely to be of some help.

Large window openings to encourage cooling air flow were thought to be a good idea but given the lack of any information on summer natural ventilation rates, this method could not be relied on. This is probably just as well, since a deeper understanding of ventilation mechanisms as explained in Chapter 9, suggests that one of the main ventilation driving mechanisms, the existence of a large temperature difference between the inside and outside of the house would be lacking in summer. Any ventilation would be totally dependent on the wind.

Thus correct orientation and thermal mass have been principally used to restrict summer temperatures. Modelling of peak summer temperatures shows that the best orientation for summer comfort coincides conveniently with that for maximum winter passive solar gains, a little east of south. (See Figure 10.13.)

Thermal mass, in the form of dense concrete blockwork has been used in the Linford houses, a poured concrete construction being used for Pennyland. The extreme calculated reduction in peak summer temperature as a result of using this construction rather than, say, timber frame lightweight construction is approximately 2°C, though given the crude one-room house model used, practical figures are likely to be much higher. The IHVE guide, for example, suggests a 6°C difference for a structure with 50% south-facing glazing (Reference 10.1). It was obviously wise to play safe.

The concrete blockwork has a cost penalty of about £70 (see Chapter 7) and also a very slight energy penalty in terms of winter energy consumption of around 100 kWh/yr, though this is very dependent on the chosen heating intermittency. This figure is nowhere near as high as some modellers have suggested (Reference 10.2) since the increased night-time temperatures and resultant energy losses are offset by an increased usefulness of solar and free heat gains.

In practice overheating has not been a problem. Peak temperatures in the occupied houses have been about 29-30°C, much as expected (see Chapter 13). Two surveys of summer temperatures at Pennyland showed a remarkable uniformity of response, with very little variation in temperature from house to house, temperatures in the single aspect Area 2 houses being about 1°C warmer on average than those for the Area 1 houses (see Pennyland report).

## 10.4. Use of Blinds and Net Curtains

The original design calculations were carried out under the naive assumption that windows were somehow 'black' and good absorbers of solar radiation. It is thus with much dismay that the actual windows of Linford and especially Pennyland have been observed to be at least 'grey' if not 'white' with net curtains, half-drawn blinds and insulating shutters.

A typical window with full net curtains appears from the outside to have approximately the same brightness as if not brighter than the surrounding brickwork, implying that at least 40% of the incident solar radiation is

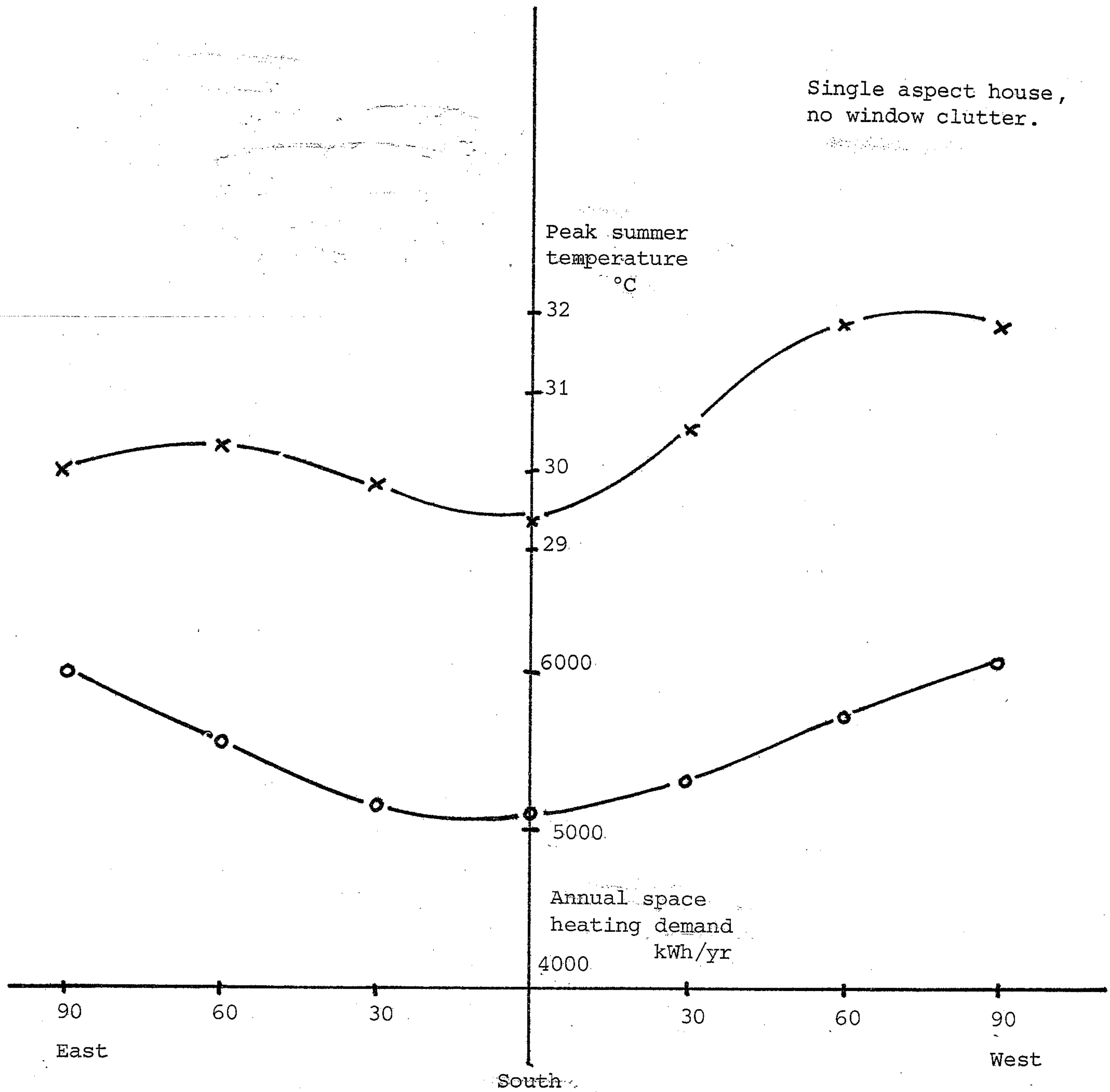



Figure 10.13 Effects of Orientation on Peak Summer Temperature and Winter Space Heating

reflected back (see Figure 10.14). The energy calculations at the end of this chapter have used solar absorptances for windows determined from test house thermal calibration experiments, with and without net curtains. Both these conditions showed considerable amounts of radiation being reflected back out of the house.

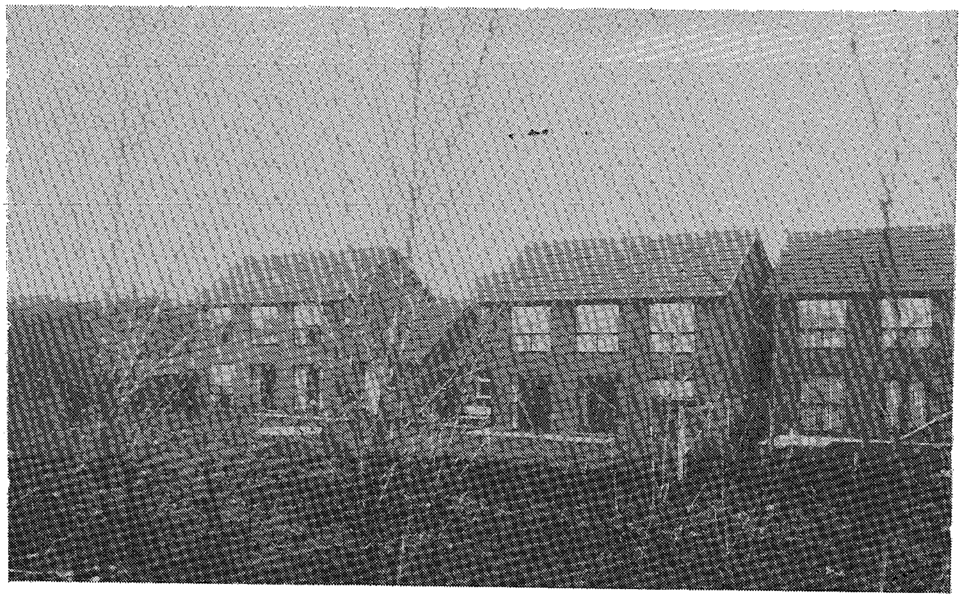


Figure 10.14 Linford Houses on a Typical Winter Afternoon

Note that about a half of the windows are lighter than the surrounding brickwork.

The half-drawn blinds and curtains may have some compensating insulating effect on the windows, but the thermal calibrations found no appreciable effect due to net curtains.

Blind and curtain use in the Linford houses was monitored by a simple visual check once per weekday morning at about 10 a.m. The number of windows covered by a blind or curtain were recorded and partially covered windows were accounted for by estimating the fraction obscured. The monthly averages of percentage obstruction for the various houses are given in the table below and also plotted in Figure 10.15.

| Month | No. of days data | House No. 33 | 34 | 35 | 36 | 38 | 39 | 40 |
|---|---|---|---|---|---|---|---|---|
| Nov. 81 | 19 | n | - | 12 | 43 | n | - | 0 |
| Dec. | 13 | n | - | 25 | 47 | n | 8 | 7 |
| Jan. 82 | 20 | n | 45 | 43 | 38 | n | 23 | 0 |
| Feb. | 20 | n | 42 | 42 | 33 | n | 7 | 2 |
| Mar. | 25 | n | 28 | 35 | 33 | n | 20 | 4 |
| Apr. | 20 | n | 28 | 30 | 30 | n | 23 | 4 |
| May | 21 | n | 7 | 2 | 20 | n | 18 | 10 |

n = full net curtains

Table 10.1 Percentage Window Obstruction at 10 a.m.

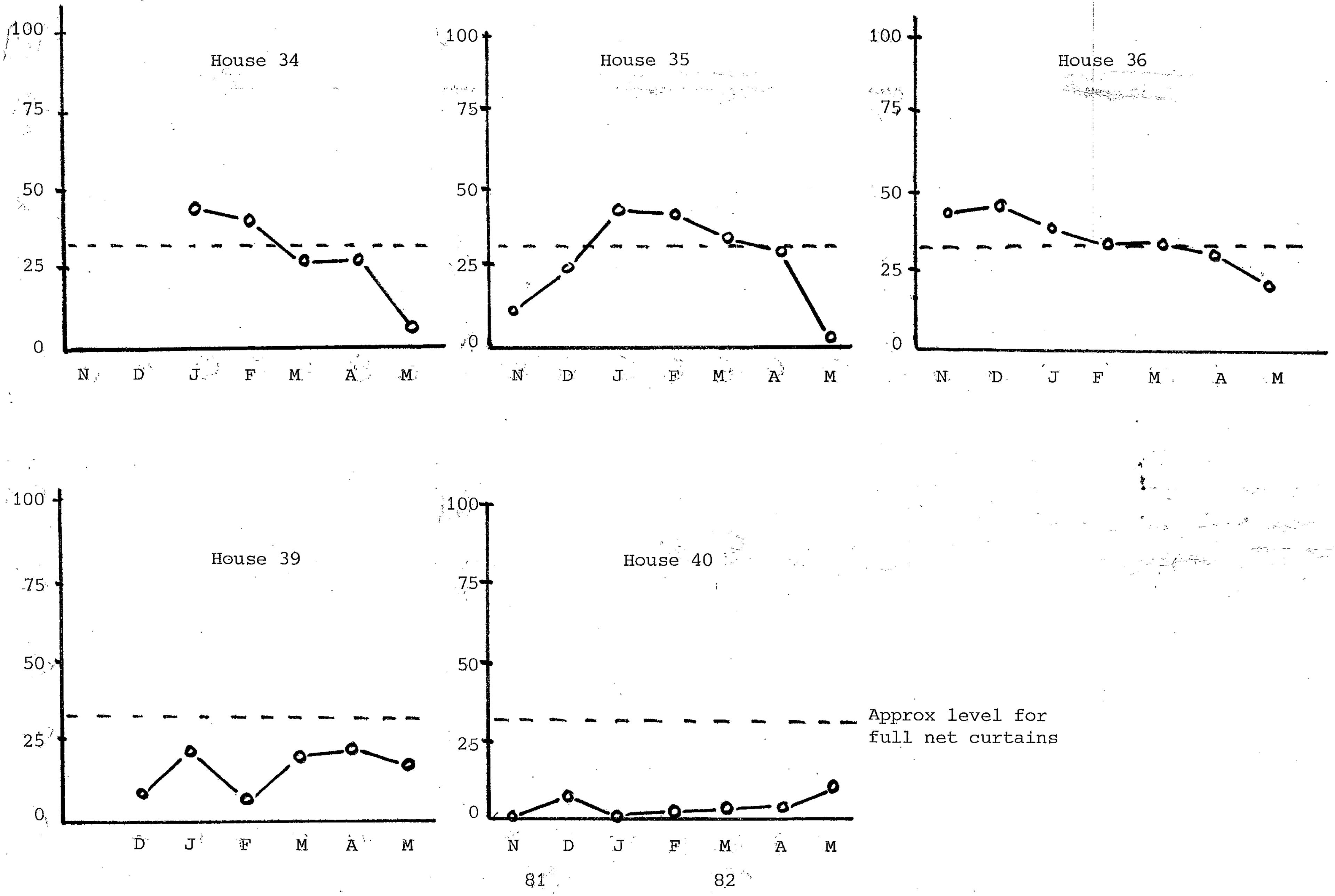



Figure 10.15 Average Percentage Obstruction of South-Facing Windows by Blinds and Curtains at 10 a.m.

The observations are somewhat limited in that it is not known whether changes were made during the rest of the day. This is perhaps likely since in the mid-winter months at 10 a.m. the sun would just be rising above the bushes to the south of the houses, as seen from the ground floor.

The patterns of use are obviously completely different from house to house. House 35 and possibly house 34 show a distinctly changing pattern of use over the heating season, suggesting that the curtains and blinds are being used as extra window insulation. House 39 and especially house 40 show very little use of blinds at all.

It is difficult to say how these percentage obstruction figures actually relate to percentage rejection of solar radiation or quite what percentage obstruction should be assigned to houses with full net curtains. A figure of 30% is probably a reasonable guess. An attempt to determine the absorptance of a window with half-drawn blinds by thermal calibration produced nonsensical results, probably due to high wind speeds at the time.

For the marginal passive solar calculations at the end of this chapter it has been necessary to choose some 'average' level of obstruction. Obviously in houses where this varies over the year, this is a little difficult. As far as total passive solar gains are concerned, the levels of obstruction at the ends of the heating season are probably the most important. The 'average' Linford house has thus been taken to have marginal passive solar gains halfway between that of a house with full net curtains and that with no curtains at all.

The Linford houses seem to have a fairly low use of net curtains compared to Pennyland. A brief survey made in March 1983 showed that 80% of the south-facing windows there had full net curtains and less than 10% no obstruction at all. The Pennyland facade shown in Chapter 2 is typical. Of the eight windows visible, six have full net curtains, one is clear and one has the paper blinds firmly drawn. The Pennyland observations are probably more typical of normal conditions since the Linford houses are not overlooked from the south.

The level of window clutter is quite important, since it leads to significant reductions in the estimates of marginal passive solar gains of the order of 30%.

## 10.5. Estimation of Solar Aperture

Measuring the performance of an active solar heating system is fairly simple, usually a matter of measuring the incident solar radiation and the flow of hot water at the output. Measuring passive solar gains quantitatively is a much more difficult task, since they are essentially a negative quantity, heating energy that has not been used.

Since weather, especially in the U.K. tends to be completely different from day to day, it is impossible to 'repeat' days with and without solar gains. It is necessary to fit some model of house heating performance such that it can be estimated on any given day what the heating requirement would have been without solar gains. This has been done for the Linford test house, where the internal temperature has been kept constant as far as possible. The results obtained do seem to agree with data from the occupied houses, taking their individual levels of window clutter into account.

At first sight it might seem that assessing the solar gains into the test house is simply a matter of calculating the shaded area of the space heating graph in Figure 10.2 and relating it to the incident solar radiation for that day. Unfortunately, not all of the shaded space heating 'saving' is caused by the direct influence of the solar radiation, a certain amount being caused by the rise in external temperature that accompanies a sunny day. This would be present even if the windows were totally reflecting. Also, it is not clear how far the exponential tail of stored solar energy extends into the next day.

The problem is thus to find:-

A. A house model simple enough to fit the measured data, both in terms of solar input and heat losses.

B. A mathematical method to do the fitting.

### 10.5.1. Choice of house model

Solar parameter

The most commonly used solar weather parameter is total radiation on the horizontal plane. However, using this to calculate solar gains through south-facing windows involves various mathematical corrections to allow for the changing altitude of the sun over the heating season. For this project measured south-facing vertical solar radiation has been used. This is a reasonable compromise between a 'meteorological' weather variable and one which accurately represents solar gains into a south-facing house.

Figure 10.16 shows daily solar gains into a Linford style house through both north and south facades calculated as a function of south-facing vertical solar radiation, both being calculated on an hourly basis from total horizontal radiation by Berlage's method (Reference 10.3). The linear relation defines a south-facing 'solar aperture' for the house, a kind of equivalent unobstructed opening through which solar gains would flow into the house.

This solar aperture is largely a mathematical tool of convenience. It is not only a function of window area, but also of the effective transmission of such things as net curtains and to a limited extent also solar gains through the opaque building fabric, though these are likely to be very small for the highly insulated Linford houses.

Given that the average incident solar radiation on the north facade of a house is about one third of that on the south facade over a heating season, the solar aperture can roughly be calculated as:-

$$\text{Solar Aperture} = A_s \times T\alpha + (A_n \times T\alpha)/3$$

where $A_s$ = Net area of south-facing glazing (excluding frames).

$T$ = Transmission of glazing, including effects of net curtains.

$\alpha$ = Absorptance of room.

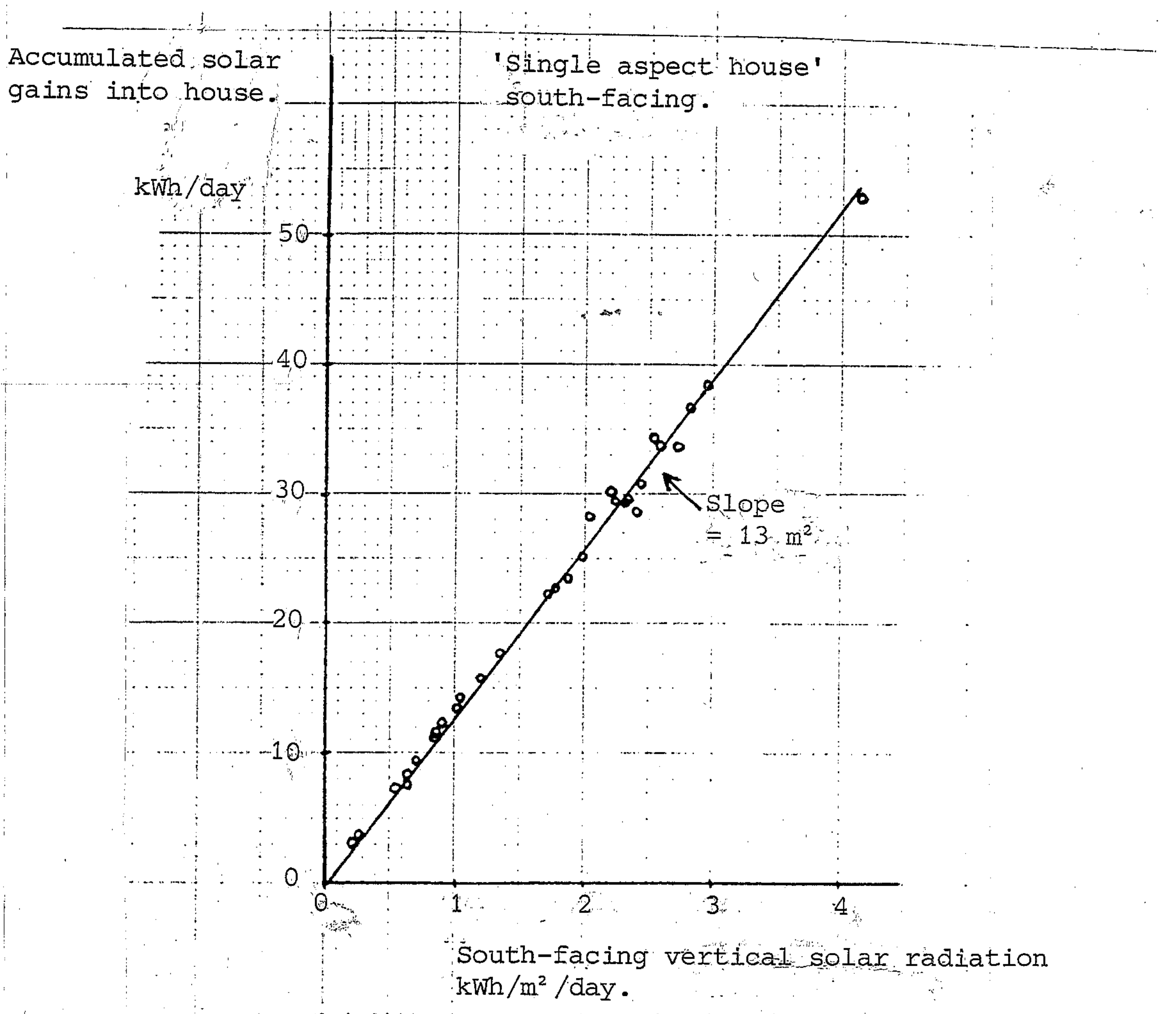



Figure 10.16 Linear Relation of Calculated Solar Gains into House with South-Facing Vertical Solar Radiation

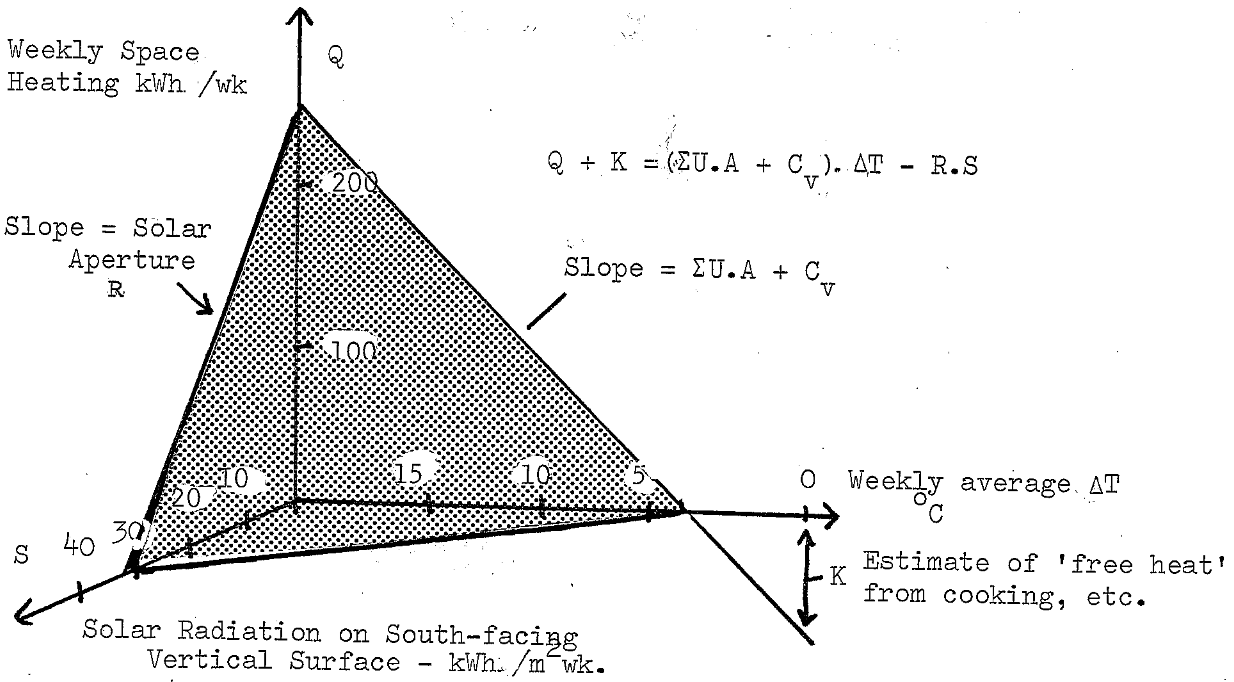



Figure 10.17 Triaxial Regression

This solar aperture is similar in function to the solar 'Recuperation Factor' used in the 'Temperature without Heating' method of analysis used in Belgium (Reference 10.4). As a result the symbol R has been adopted for the solar aperture though not being precisely equivalent to the Recuperation Factor.

Heat losses

It was initially hoped that the crudest of house U-value models would suffice and that the house heat loss could be expressed in simple terms as:

$$\text{Heat Loss} = (\Sigma U.A + C_V).\Delta T$$

where $\Sigma U.A.$ = Total house fabric heat loss, (including floor)
$C_V$ = House ventilation rate (assumed constant)
$\Delta T$ = Average inside-outside air temperature difference.

In practice it has been found necessary to split the house heat losses into three parts, the ventilation loss, the floor loss and the remaining fabric loss.

Although the ventilation loss is fortunately rather small in the Linford houses, it does fluctuate widely from day to day with wind speed and, in the occupied houses, with window opening (see Chapter 9).

The floor heat loss, as explained in Chapter 8, may not be proportional to the measured external air temperature, but related to a slowly moving ground temperature lagging about a month behind the average air temperature.

The fabric loss through walls, roof and windows can be taken to be proportional to the measured inside-outside air temperature difference though some correction for thermal time-lags may be necessary for short timescales, such as daily average data.

## 10.5.2. Analytic methods

Basically two analytic methods have been tried, multivariate regression analysis or 'triaxial regression' and a simpler two dimensional method suggested by Siviour (Reference 10.5).

Triaxial Regression

Using the crude house model suggested above and working, say, on a weekly basis, the house heat balance can be written:

$$Q + K = (\Sigma U.A + C_V).\Delta T - R.S$$

where $Q$ = Weekly space heating.
$K$ = Free heat gains from cooking, lights, etc.
$\Sigma U.A$ = House heat loss including the floor.
$\Delta T$ = House weekly average inside-outside temperature difference.
$R$ = Solar aperture.
$S$ = South-facing solar radiation.

Using least-squares regression analysis, correlating Q against $\Delta T$ and S, it should in theory be possible to extract values for $\Sigma U.A + C_V$, R and K. The process is equivalent to fitting a mathematical plane through the data lying in 3-dimensional space between three axes of Q, $\Delta T$ and S (see Figure 10.17), hence 'triaxial regression'.

It was found that even with good quality test house data, where the internal temperature was kept constant and the free heat gains should be zero, that this method simply did not work. The possession of good data and an analysis method did not guarantee answers. It was found that it was necessary to undertand how the regression process extracted these answers and its consequent data needs. After much study, including plotting data out in three dimensions, both physically and using computer graphics, this method was abandoned.

Briefly the basic reasons for abandoning this method were as follows:

1. Least-squares regression is very sensitive to 'outliers' or extreme data points. As a result it is very important to work with 'clean' data in which recording errors and, in the case of the occupied houses, anomalous behaviour periods such as holidays have been weeded out. This cleaning process involves a lot of visual inspection of the data. This is a little difficult if the data consists of points lying in three-dimensional space. The problem also extends to non-linearities such as end of heating season window opening and the dependence of ventilation rates on $\Delta T$, etc. Without the ability to visually inspect the data, it becomes very difficult to understand what is actually happening.

2. Many typical data sets have very small variations in $\Delta T$. The U.K. weather is not prone to violent swings in temperature and day-to-day or even week-to-week variations in external temperature are only likely to be 5°C or less. For occupied houses of the Linford type, with high levels of solar gains, the heating season proper may not actually start until average $\Delta T$'s approach 10°C. This poor spread in values of $\Delta T$ has led to poor estimates of $\Sigma A.U$ and in particular the free heat gains, K. In this case, the estimate has typically been so bad that almost any reasonable guess by a researcher would have been better.

There are other reasons, but these also apply to the second method tried.

It became clear that statistics were no substitute for understanding. In particular, it was apparent that in order to extract important quantities such as the fabric heat loss and the solar aperture it was necessary that the right weather conditions are included in the data sets, and that the right model is being used to fit the data.

Siviour's method

This is a transformation of the triaxial regression above into a two-dimensional form. This has the great benefit of allowing the data to be plotted out on paper, rendering some of the statistical problems immediately visible.

Given the heat balance equation

$$Q + K = (\Sigma U.A + C_V).\Delta T - R.S + F$$

where F is the floor heat loss, treated separately. Taking K, F and $C_V$ as known, rather than unknown quantities, it can be rewritten

$$\frac{(Q + K - F)}{\Delta T} - C_V = \Sigma U.A - R.S/\Delta T$$

Thus by plotting $(Q + K - F)/\Delta T - C_V$ against $S/\Delta T$, we get a graph whose Y-intercept is $\Sigma A.U$ and whose slope is R, the solar aperture.

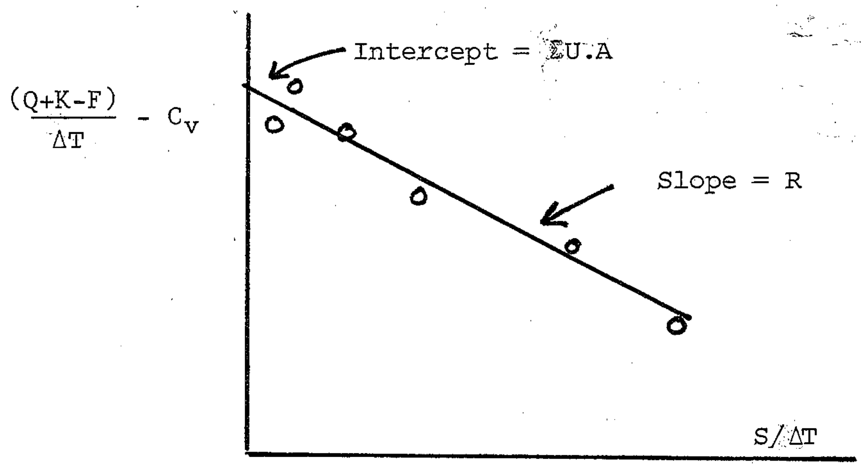



Figure 10.18 Two-Dimensional Regression Plot

This plot has been used, with minor variations, for the determination of solar apertures and fabric heat losses for both the test house and the occupied houses.

Although it is actually a mathematical transformation of the triaxial regression, it can be thought of as being roughly equivalent to a projection of the data, edge on to the fitted plane, back on to the surface bounded by the Q and S axes of Figure 10.17. If $\Delta T$ does not vary much over the data set, and can thus be thought of as a constant, it is exactly equivalent.

10.5.3. Accelerated thermal calibration project

The above method was originally suggested simply for the estimation of the fabric heat loss of a test house, using weekly data (see Reference 10.5). This would require four or five dull mid-winter weeks, with low values of $S/\Delta T$, to give a good fix on the Y-intercept, and one or two sunnier weeks to fix the solar slope.

In October 1981, a brief one-week thermal calibration was carried out on a small terrace house with a conservatory, situated in north Milton Keynes. Analysis of this data showed that it was possible to extract a figure for the solar aperture using daily rather than weekly data, provided that corrections were made to compensate for thermal lag effects in the building fabric (see Reference 10.6).

Given the potential to drastically reduce the time taken to assess the thermal performance of a house, and the imminent availability of data from the Linford test house, extra funding was sought from the Science and Engineering Research Council. This was for an assessment of 'Accelerated Thermal Calibration of Houses', aiming to reduce the required experimental period from six or seven weeks down to two or less.

Funding for this project eventually started in January 1983, though much of the experimental material actually predates this. The results in this section are largely a summary of work carried out under this contract. Full details will be published in a separate thermal calibration report at a later date.

### 10.5.4. Regression data requirements

The Linford test house was ready for thermal calibration experiments in March 1982. It was kept at a constant internal temperature of 22°C by five electric fan heaters with electronic thermostats and air infiltration measurements were made continuously. Analysis of weekly data for March and April 1982 using the triaxial regression method was not very fruitful. The data set suffered from small spreads of both $\Delta T$ and solar radiation, and worst of all, a large and rapidly varying floor heat loss (see Chapter 8). This changing floor loss led to a very high estimate of the solar aperture and illustrated the problems of using statistics without really understanding either the statistical method or the physical processes at work in the house.

More detailed work on a two-week segment of this dataset has been more forthcoming. The raw data for part of this period in March 1982 is shown in Figure 10.19 and includes the days shown in figures 10.2 and 10.3, giving a longer time perspective. The actual period was chosen to give the best mix of sunny and dull days, since it is by comparing space heating on the two that the solar aperture is essentially determined.

Measured air infiltration rate is shown as well as space heating, solar radiation and temperatures. It has been expressed as six-hour averages for ease of calculation, since the actual time period of measurement depends on the air change rate (see Chapter 9). The infiltration rate is almost constant over the dataset at about 0.5 ac/hr but does briefly rise to 1 ac/hr on a windy day.

Although there are wide excursions of external air temperature during the day, actual daily average temperatures are almost all the same, about 7°C. Obviously there is not much hope of determining the house heat loss by comparing space heating on warm and cold days.

Largely as a result of studying this dataset, a series of data requirements have been drawn up in order to carry out a thermal calibration. Briefly it would appear that it is possible to get a reasonable estimate of the fabric heat loss of a house and its solar aperture given two weeks data provided that:-

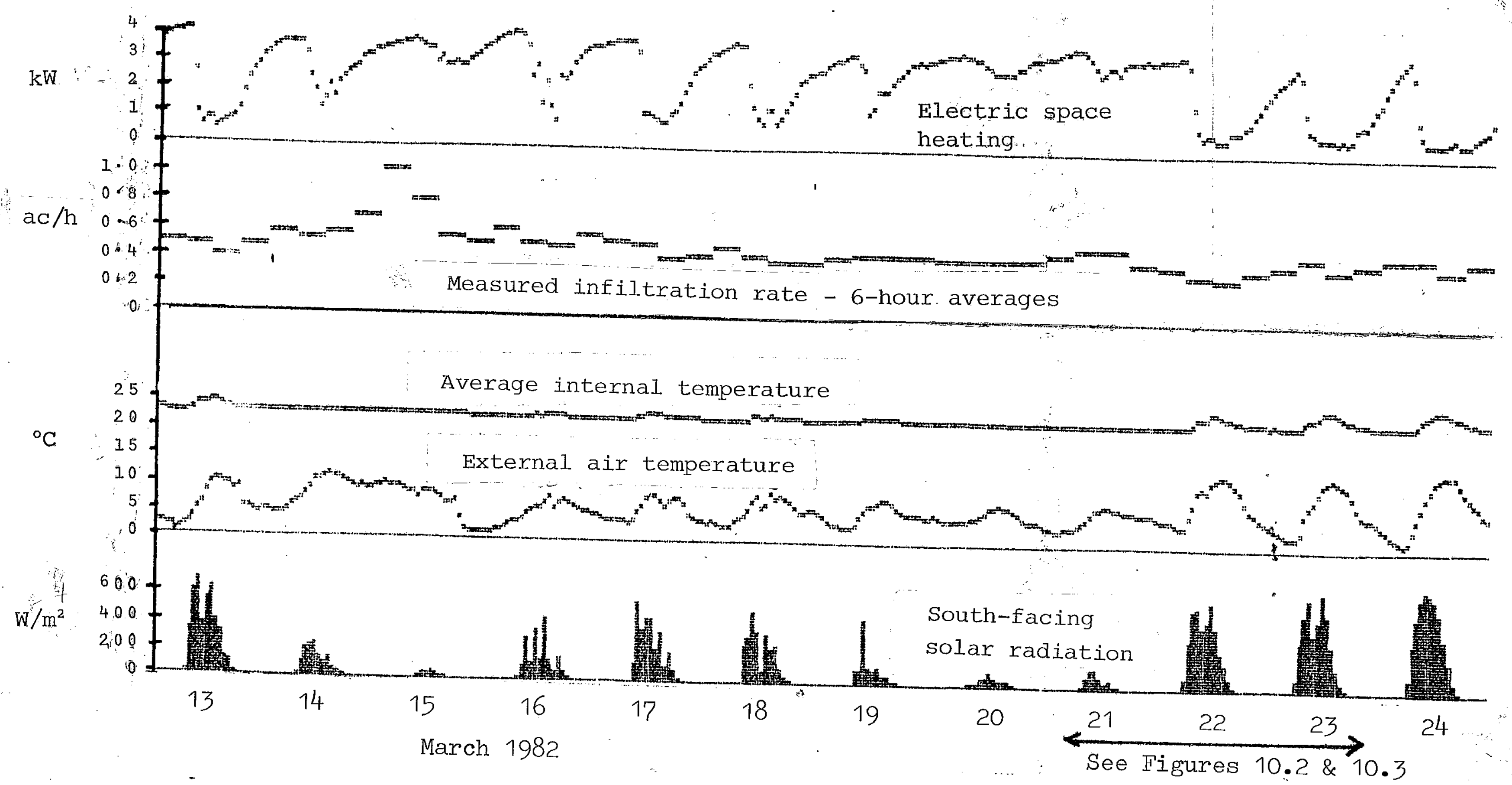



Figure 10.19 Space Heating, Infiltration, Temperatures and Solar Radiation 13.3.82 - 24.3.82

1. There is a good mix of sunny and dull days. The dull days give a good fix on ΣU.A and the sunny ones allow the calculation of the solar aperture. The need for dull days tends to limit the whole process to the months October to March, since sunny days seem available all year round, but dull ones are rare in summer.

2. Air infiltration should be measured, since it can vary widely over the experimental period.

3. The floor heat loss should be estimated separately, since it is not directly related to measured external air temperature.

4. 'Days' should run from dawn to dawn rather than midnight to midnight in order to allow any solar gains that have gone into storage in the building fabric the maximum amount of time to emerge and displace space heating.

These four requirements on their own are fairly easy to implement and likely to give reasonable results. In addition, there are three others of a more mathematical nature. They are, in order of decreasing importance:-

5. Corrections should be made for thermal time-lags in the house to changes in external temperature. This involves calculating the daily average external air temperature incorporating air temperatures from the previous day. This 'external weighting' involves an assumed response factor model of the building fabric.

6. Corrections should also be made in a similar fashion for the slight day-to-day changes in internal temperature, notably the mid-day rises in temperature that accompany a very sunny day, forcing solar radiation into storage in the walls. This 'internal weighting' process involves assuming a model of the thermal mass of the house as it interacts with solar gains and is consequently rather dubious in practice. Also, for day-to-day solar energy storage reasons, it is desirable to delete from the dataset very dull days that are preceded by a run of sunny days.

7. The co-variance of solar radiation and ΔT should be restricted in order to prevent errors in determining the floor heat loss or the infiltration rate appearing as solar aperture. This problem is unlikely to be serious in practice since short-run datasets seem to exhibit little variation in ΔT. In summer sunny days tend to be warmer than dull days, in winter the reverse is true. During spring and autumn there is little difference.

These data requirements are dealt with in greater detail in the separate thermal calibration report.

Figure 10.20 shows the raw data of Figure 10.19 expressed as a thermal calibration plot using these suggestions. This calibration gives a fabric heat loss of 127 ±5 W/°C and a solar aperture of 9.8 ±0.6 $m^2$. The error bars denote the range over which there is a 68% probability that the true answer lies. These are merely statistical errors of interpreting the data points as plotted, and do not include measurement errors, which, as pointed out in Chapter 8, can be considerable.

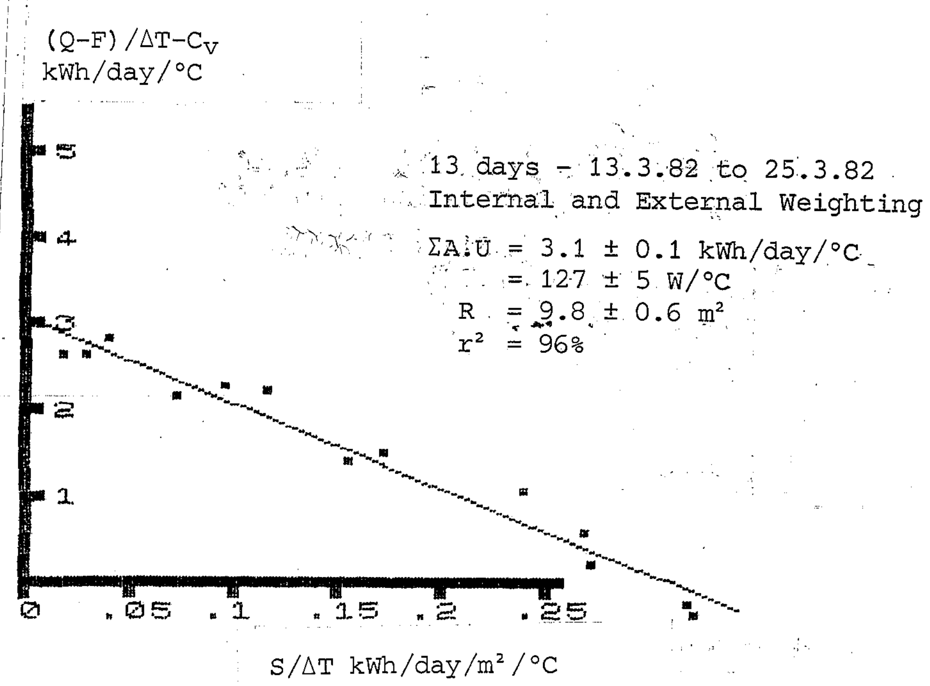



Figure 10.20 No Curtains - Floor Uninsulated

10.5.5. 82/83 heating season programme

The thermal calibration process was extended over the winter of 1982/83. The internal temperature was raised to 25°C to extend the heating season as far as possible. This high internal temperature also had beneficial effects in reducing mid-day overheating and consequent energy storage effects, enabling 'internal weighting' and its dubious assumptions about the thermal mass of the house to be dispensed with.

Two modifications were made to the floor surface over the period. At the end of October 1982 the floor was covered with carpet tiles to bring test house conditions more into line with those in the occupied houses. In mid-December the floor was insulated over with 50 mm polystyrene. The prime reason for doing this was to obtain estimates for the test house solar aperture free from interference from changing floor heat losses, though as described in Chapter 8, it has provided an interesting experiment in its own right.

In addition to these floor insulation variations three solar variants were tried out:

1. Full clear window area.

2. Full net curtains.

3. Half net curtains, half white card.

These were run in a cyclic fashion of approximately two-week periods as shown in Table 10.2, allowing assessments over a wide range of temperatures and solar inputs. Air infiltration measurements were only made for a part of the time. It was not fully realised how important these measurements are to accurate thermal calibration and the lack of them has led to some data sets being abandoned. However, as second best, there were sufficient measurements to create a model relating air infiltration to wind speed, direction and measured house $\Delta T$, as described in the previous chapter. This did allow the prediction of infiltration rates for any hour of the year from measured weather variables, although of limited accuracy, typically ±30%.

Results

The ten separate periods of the 82/83 season obviously provide enough data for pages of graphs. These have, indeed been produced in order to test the self-consistency of the thermal calibration method, whether or not it can produce the same answers for a given house variant given different weather conditions. Fortunately the data sets for the first two solar variants consistently gave similar values of solar aperture. The data for the last variant, half net curtain, half white card had to be abandoned as containing too much windy weather for the infiltration predictions to be reliable.

Successive estimates fabric heat loss were not altogether consistent and this, as mentioned in Chapter 8, appears to be due to errors in determining the floor heat loss.

The solar performance of the test house can thus be summarised in four graphs showing solar apertures with and without net curtains, and with and without floor insulation. Including Figure 10.20 already shown, the remaining variants are plotted in Figures 10.21-23.

| Variant | Apparent Fabric Loss | Solar Aperture |
|---|---|---|
| Floor uninsulated no curtains | 127 ± 5 W/°C | 9.8 ± 0.6 m² |
| Floor uninsulated (with carpet) net curtains | 137 ± 3 W/°C | 8.1 ± 0.6 m² |
| Floor insulated no curtains | 155* ± 2 W/°C | 10.1 ± 0.6 m² |
| Floor insulated net curtains | 148* ± 3 W/°C | 8.0 ± 0.6 m² |

*probably overestimates due to errors in floor loss measurement.

Table 10.2 Test House Constant Temperature Heating Tests

| Period | Floor Condition | Window Condition | Ventilation | Internal Temp. |
|---|---|---|---|---|
| 25/2/82 - 4/5/82 | Uninsulated Bare | Full Area No curtains | Measured* 52 Days | 22°C |
| 11/10/82 - 27/10/82 | Uninsulated Bare | Full Area No Curtains | Predicted | 25°C |
| 30/11/82 - 10/11/82 | Uninsulated Carpet | Full Area No Curtains | Predicted | 25°C |
| 12/11/82 - 13/12/82 | Uninsulated Carpet | Full Area Net Curtains | Predicted Measured 13 Days | 25°C |
| 16/12/82 - 1/1/83<br>26/1/83 - 10/2/83 | Insulated | Full Area No Curtains | Predicted<br>Measured 6 Days | 25°C |
| 2/1/83 - 13/1/83<br>11/2/83 - 3/3/83<br>4/4/83 - 31/5/83 | Insulated | Full Area Net Curtains | Predicted<br>Measured 14 days<br>Predicted | 25°C |
| 14/1/83 - 25/1/83<br>4/3/83 - 15/3/83 | Insulated | Half area Net curtains<br>Half area white card | Predicted | 25°C |

*only included where there are more than 4 samples/day

The essential conclusions from these results are that:-

1. Insulating the floor makes no apparent difference to the solar aperture. This is not particularly surprising given the already noted poor solar absorptance of the floor surface.

2. The solar aperture without net curtains is about 10 $m^2$ and with net curtains about 8 $m^2$. The error margins on these are fairly large. The quoted errors are the interval over which there is a 68% confidence that the true answer lies. The 90% confidence interval is about ± 1 $m^2$.

The figure of 10 $m^2$ for clear windows is considerably less than the calculated solar aperture of 13 $m^2$ produced from measured glass areas (see Figure 10.16). Even this figure does not include possible solar gains absorptance can be ascribed to three reasons:

1. Shading effects of the roof eaves and window reveals, not included in the original calculation.

2. Reflection of radiation back from the interior of the house.

3. A problem of definition of air temperature.

This last reason requires a little explanation. The thermal calibration process assumes that a house loses heat to some kind of measured external air temperature. The measured temperature used for the calculations is a Stevenson Screen temperature. Although this is normal practice it is not a true air temperature and will vary with incidental solar radiation. It is possible that this effect could account for 0.5-1 $m^2$ of the discrepancy in solar apertures (see Appendix 10.3).

### 10.5.6. Comparison with occupied houses

The regression procedure has been extended to the occupied houses. Here, lacking actual measurements, the floor and ventilation losses have been estimated and careful account has been taken of free heat gains. Also, given slight day-to-day variations in internal temperature a longer regression timescale has been used.

#### Free heat gains

These have included gains from electricity use, occupants body heat, hot water cylinder heat losses, boiler casing heat losses and gains from hot water use. The details are described in Chapter 11.

#### Floor heat loss

This has been taken as equivalent to a U-value of 0.9 $W/m^2\,°C$ between the measured living room temperature and the assumed sinusoidal ground temperature suggested in Chapter 8.

## Test House Correlations

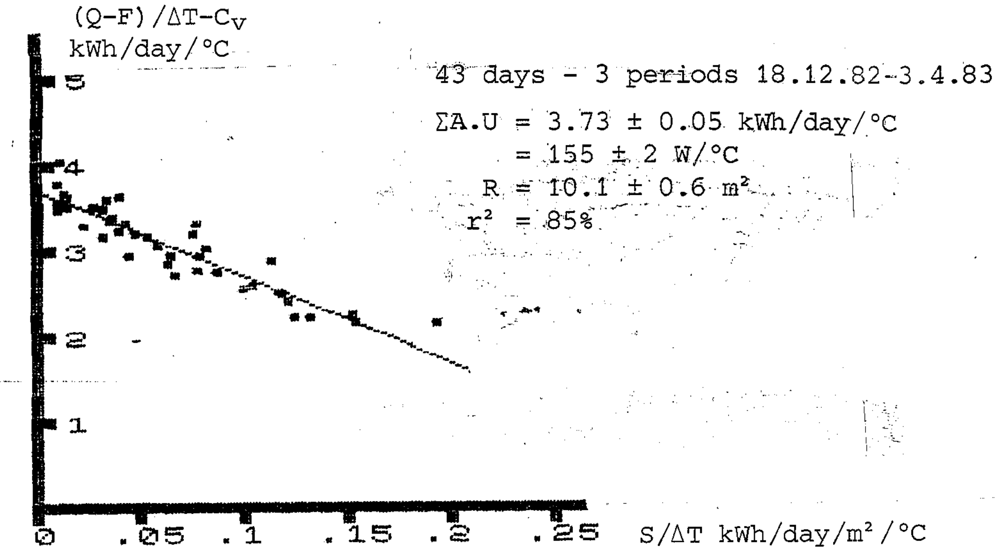



Figure 10.21 No Curtains - Floor Insulated

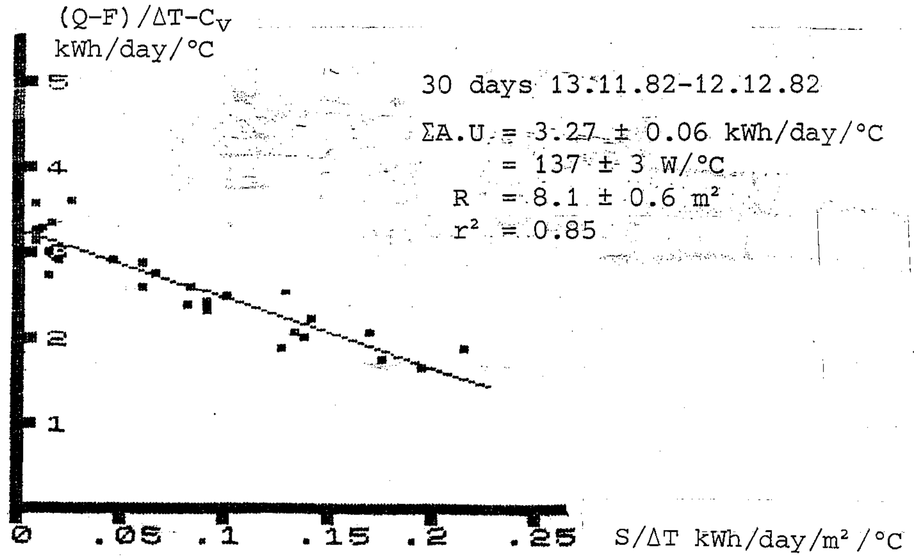



Figure 10.22 Net Curtains - Floor Uninsulated

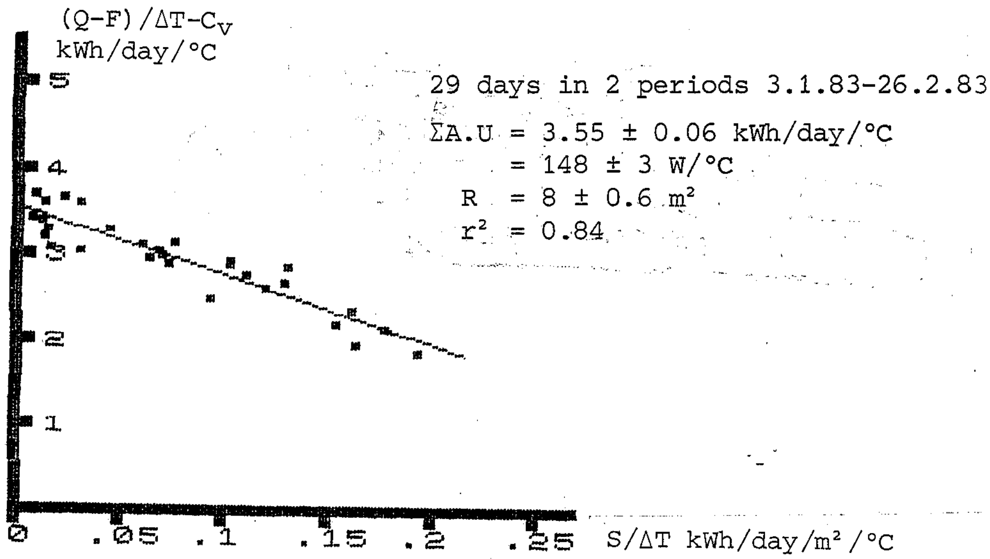



Figure 10.23 Net Curtains - Floor Insulated

Ventilation loss

The hourly air infiltration model of the test house has been extrapolated to the occupied house by scaling by their measured pressure test air leakages. In addition corrections have been added proportional to measured window opening to give the overall hour by hour ventilation rate. This process is described in Chapter 9.

Regression timescale

Studies of test house data show that once the floor and ventilation losses are properly dealt with regression timescale is not such a problem. Consistent answers can be obtained from daily, 2-daily and weekly regressions. The timescale used for the occupied houses has been six-day averages, chosen to give the best trade-off between day-to-day energy storage effects and a good spread of values of $S/\Delta T$.

Co-variance of S and $\Delta T$

As previously noted it is desirable to restrict the co-variance of S and $\Delta T$. Fortunately, given fast computer graphics, it has been easy to visually check this and to split the plots into 'bands' of different $\Delta T$'s to see if the regression line differs.

Results

The regression lines for four of the occupied houses are shown in Figures 10.24-27. Given the large number of assumptions about free heat gains, the quality of fit to a line is extremely good, in fact as good as the short-run test house data. The solar apertures and apparent fabric heat loss figures are given in Table 10.4 below.

Table 10.4 Occupied House Results

| House No. | Window Condition | Apparent Fabric Heat Loss kWhr/day $^{\circ}$C | W/$^{\circ}$C | Solar Aperture $m^2$ |
|---|---|---|---|---|
| 33 | Full net curtains | $3.11 \pm 0.08$ | $130 \pm 3$ | $6.8 \pm 0.6$ |
| 35 | Clear - moderate curtain use | $3.10 \pm 0.14$ | $129 \pm 6$ | $9.4 \pm 0.8$ |
| 36 | Clear - moderate curtain use | $3.33 \pm 0.15$ | $139 \pm 7$ | $10.7 \pm 1.0$ |
| 38 | Full net curtains | $3.96 \pm 0.11$ | $165 \pm 5$ | $7.9 \pm 0.8$ |

LINFORD OCCUPIED HOUSE CORRELATIONS

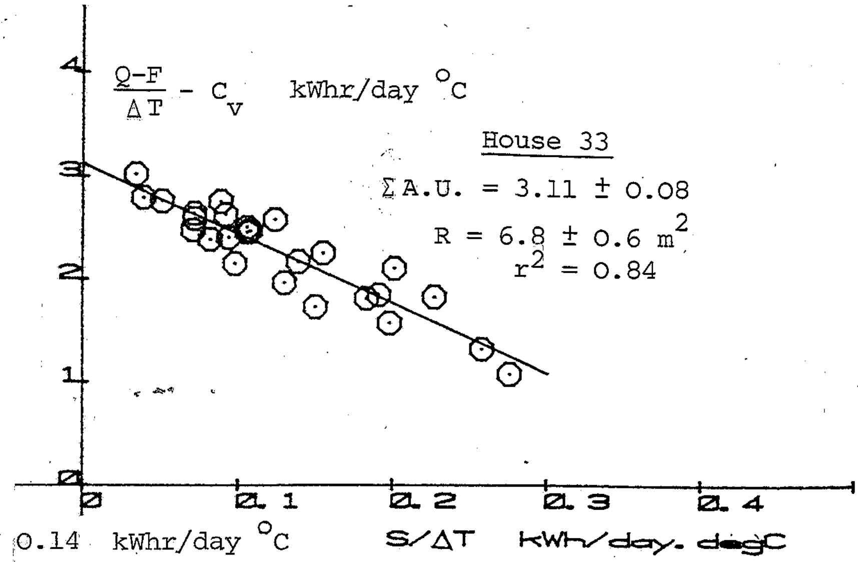



Figure 10.24

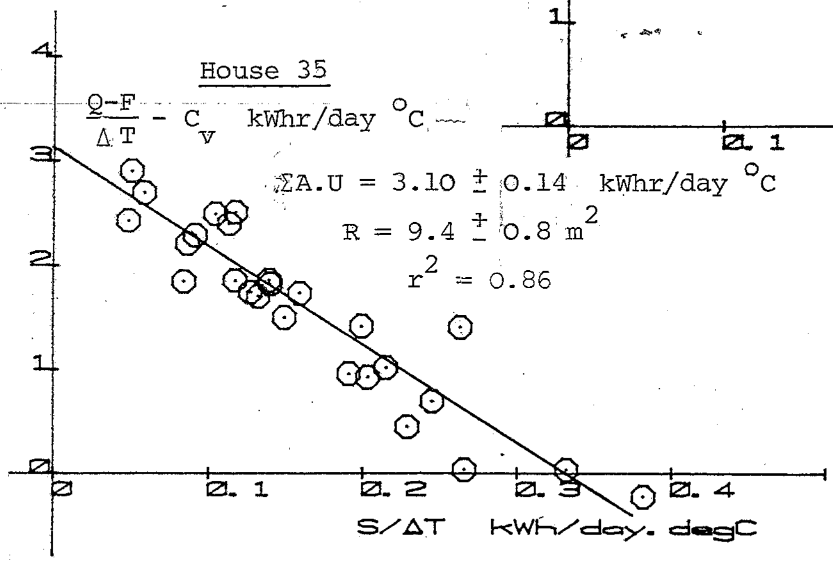



Figure 10.25

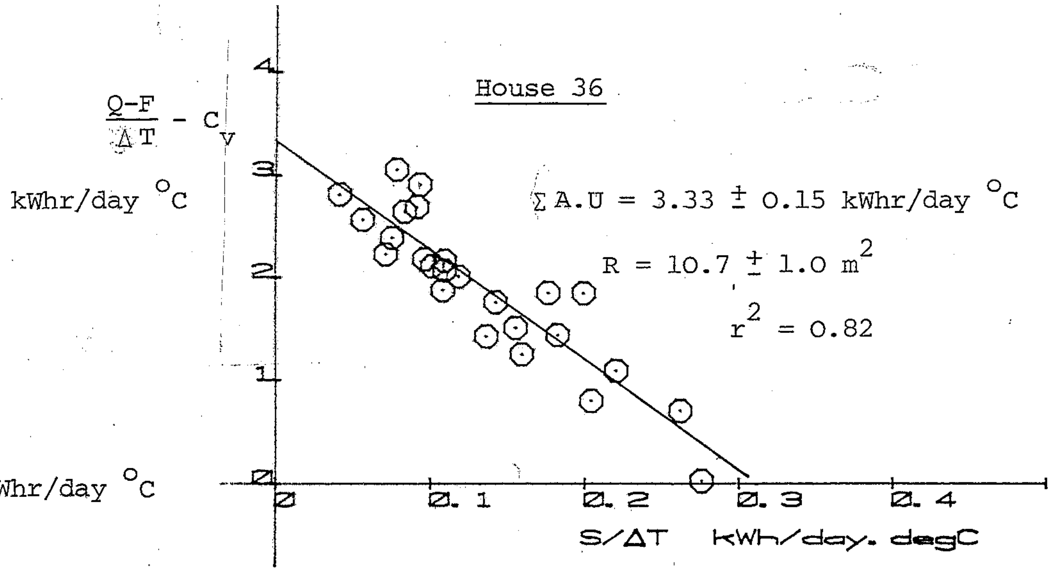



Figure 10.26

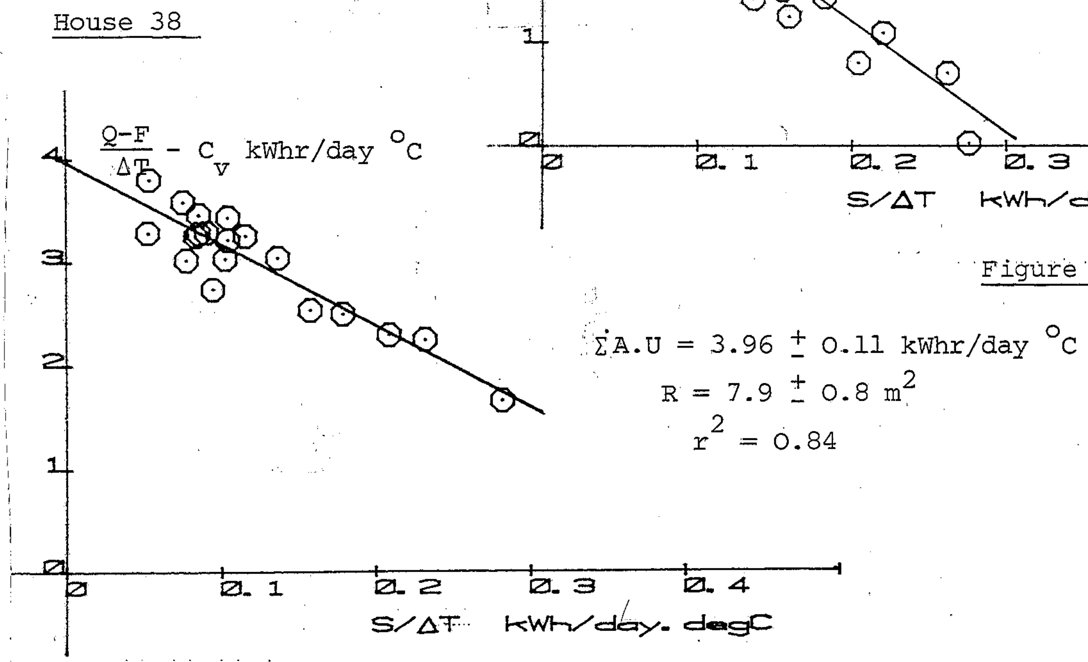



Figure 10.27

The apparent solar apertures are quite compatible with the test house results of 8 m² for a house with net curtains and 10 m² for one without. The high solar apertures for houses 35 and 36 would perhaps indicate that the closed curtains mentioned in Section 10.4 are not as serious a problem as might seem at first sight.

The apparent fabric heat losses for three of the houses are quite in agreement with the test house values of just over 130 W/°C, suggesting a certain uniformity of construction. The value for house 38 is significantly larger, though this may be due to errors in determining the ventilation loss or free heat gains, rather than any genuine difference in thermal performance. The fabric losses determined from these regressions have been used in Chapter 12 to build up the house energy balances and hence the annual absolute solar gain contributions.

This process of fitting essentially a simple U-value model to occupied house data is in a way mildly revolutionary, since it has been widely held that it is impossible to make 'sense' of occupied house energy consumptions.

## 10.6. Calculation of Annual Solar Gains

The solar parameter that has been measured in this project is the test house solar aperture, its response to daily and weekly inputs of solar radiation. These measurements have been shown to be compatible with similar estimates from the occupied houses.

This solar aperture can be turned into two quantities that are meaningful in annual energy terms. The first is the absolute seasonal solar gain, the total amount of solar energy that can be considered useful in heating the house over the year. The second, more important, quantity is the marginal seasonal solar gain, i.e. how much less space heating energy a 'solar' house uses than a 'non-solar' one at the same insulation level.

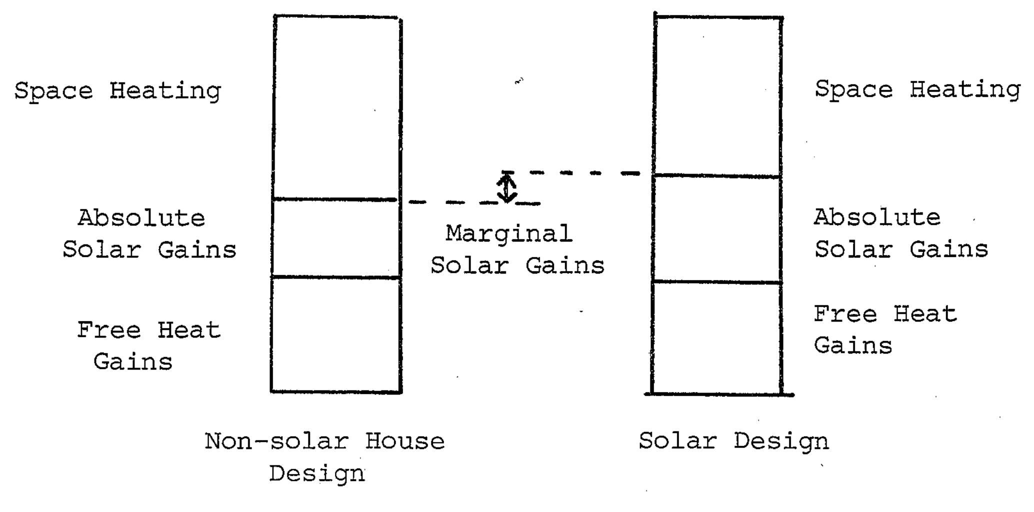
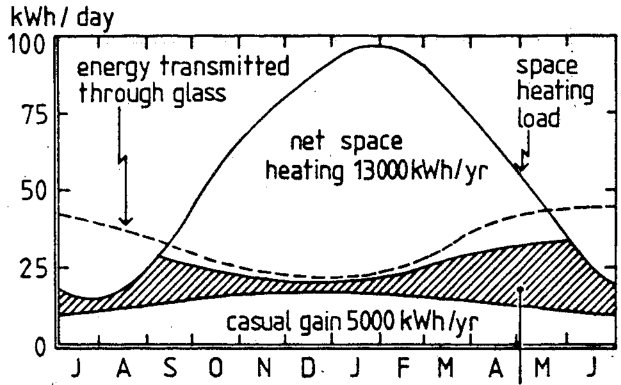



Figure 10.28 Absolute and Marginal Passive Solar Gains

## 10.6.1. Absolute seasonal solar gain

This is the total amount of solar energy that is used in either displacing space heating over the year or in creating 'useful' rises in internal temperature. By convention solar energy is only taken to be useful after free heat gains from cooking, etc. have been taken into account.

It is a quantity that is very dependent on the length of the heating season, which is in turn a matter of insulation standard, internal temperatures and free heat gains. It is not, though, a figure of merit for the house. Figures 10.29 and 10.30 show annual energy balances for two houses, one to the 1976 Building Regulation insulation standards and one to the Linford standard. These show that although the more highly insulated house has the lower space heating demand it also has the lower absolute solar gain, because of the contraction of the length of the heating season.




Absolute solar gain 3000kWh/yr

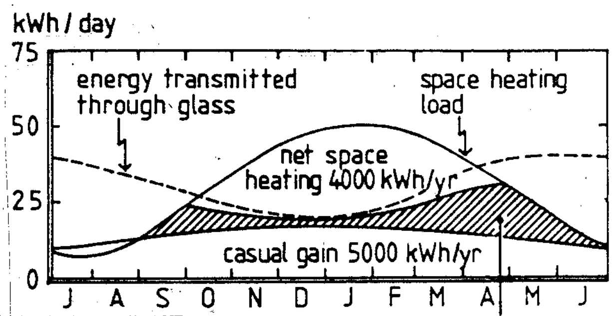
Figure 10.29

HEAT SUPPLY AND DEMAND FOR 3 BEDROOMED HOUSE, BUILT TO 1976 REGULATIONS.

| | |
|---|---|
| Windows, Walls | 1·8 W/m$^2$K |
| Roof | 0·6 |
| Floor | 1·0 |

Average internal temperature 18°C

Source: Electricity Council Research Centre "Houses as Passive Solar Collectors" ref.10.8.




Absolute solar gain 2000 kWh/yr

Figure 10.30

HIGHLY INSULATED HOUSE (reduces heating season and hence solar contribution – compare with poorly insulated house.)

| | |
|---|---|
| Windows | 2·5 W/m$^2$K |
| Walls, Roof, Floor | 0·3 |

Average internal temperature 18°C

Even where the glazing areas have been increased to capture more solar gains, a high level of absolute solar gain may be no mark of a low energy house. As one U.S. writer put it, "Most solar heating systems of the passive type create big heat losses, and then provide about enough heat to make up these losses. If you use percent solar heating as a criterion, you call such houses great successes. But if you focus your attention on what really counts, the cost of back-up heat needed, you may find many of these houses to be failures." (Reference 10.7.)

The absolute seasonal solar gains of the Linford occupied houses have been calculated in Chapter 12, giving values between 2800 kWh/yr and 4400 kWh/yr. The calculation process does illustrate the problems that arise in defining precisely what is 'useful' extra temperature and consequently how long the heating season really is.

10.6.2. Marginal passive solar gain - calculation method

This is the difference in annual energy consumption between two house designs with identical insulation levels but with different passive solar features. For the purposes of this project, these have been restricted to:

1. Avoiding overshading.

2. Correct orientation.

3. Concentrating the glazing area on the south side, without changing the total area.

4. Avoiding window clutter.

Actual measurements at Linford are, of course, restricted to one house type, exhibiting a range of degrees of window clutter. The process of calculating marginal energy savings can only be done by thermal modelling and in particular creating models of houses that do not physically exist.

For the purposes of this modelling exercise, four house types have been defined:

1. A 'normal' overshaded dual aspect house (i.e. with equal glazing areas on both facades). 'Normality' includes full net curtains.

2. A south-facing non-overshaded dual aspect house with net curtains.

3. A south-facing non-overshaded single aspect house, i.e. Linford as built, with net curtains.

4. As above, but with clear windows.

A marginal passive solar gains have been calculated essentially as the differences in annual energy consumption between these four house types (see Figure 10.31). The calculation process has been carried out using the NBSLD-based model, adjusted as far as possible to correspond to typical Linford house performances. This has involved drawing together information from both the test house and occupied house studies, as well as material from outside (see Figure 10.32).

The fabric and ventilation losses have been adjusted to the assumed 'average' figures as summarised in Chapter 8, in particular in Table 8.2 and Figure 8.19.

Figure 10.31 Passive Solar Steps

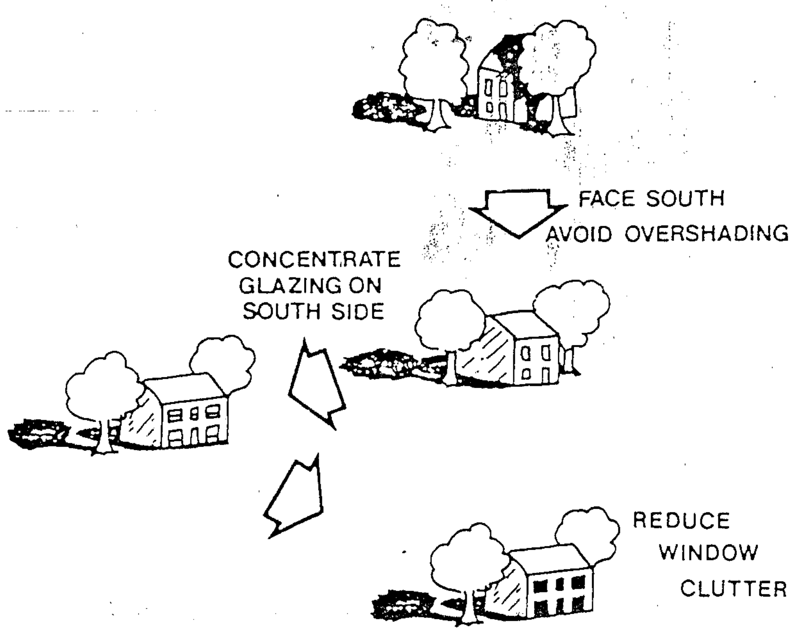
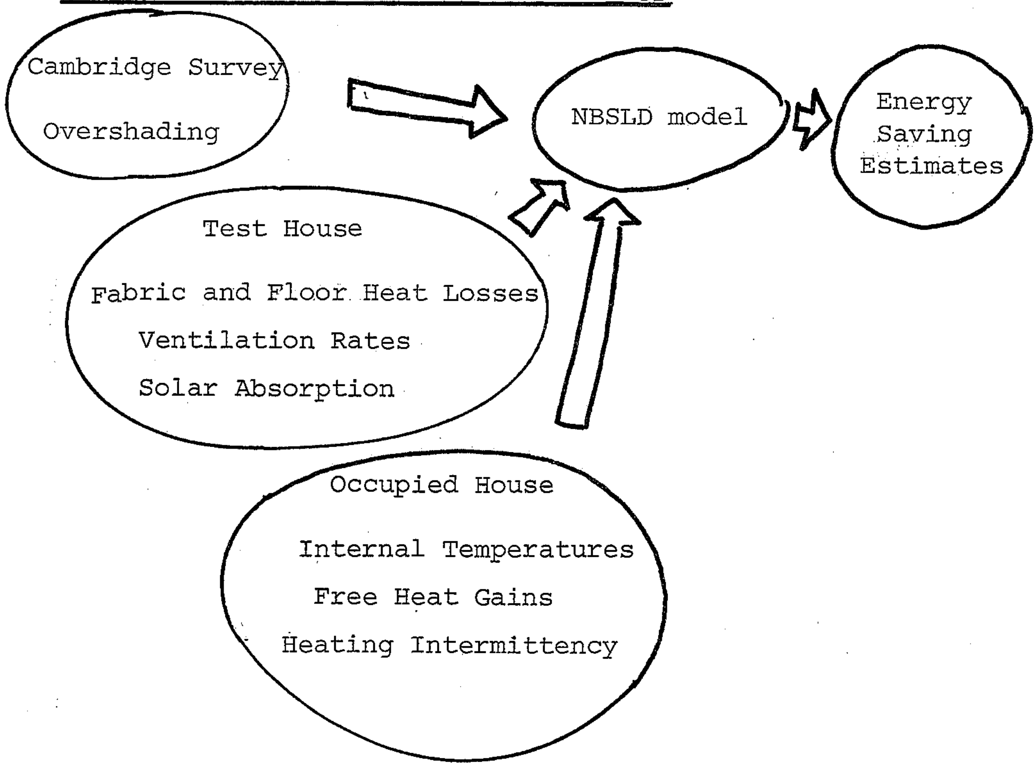



Figure 10.32 Comparison Methodology



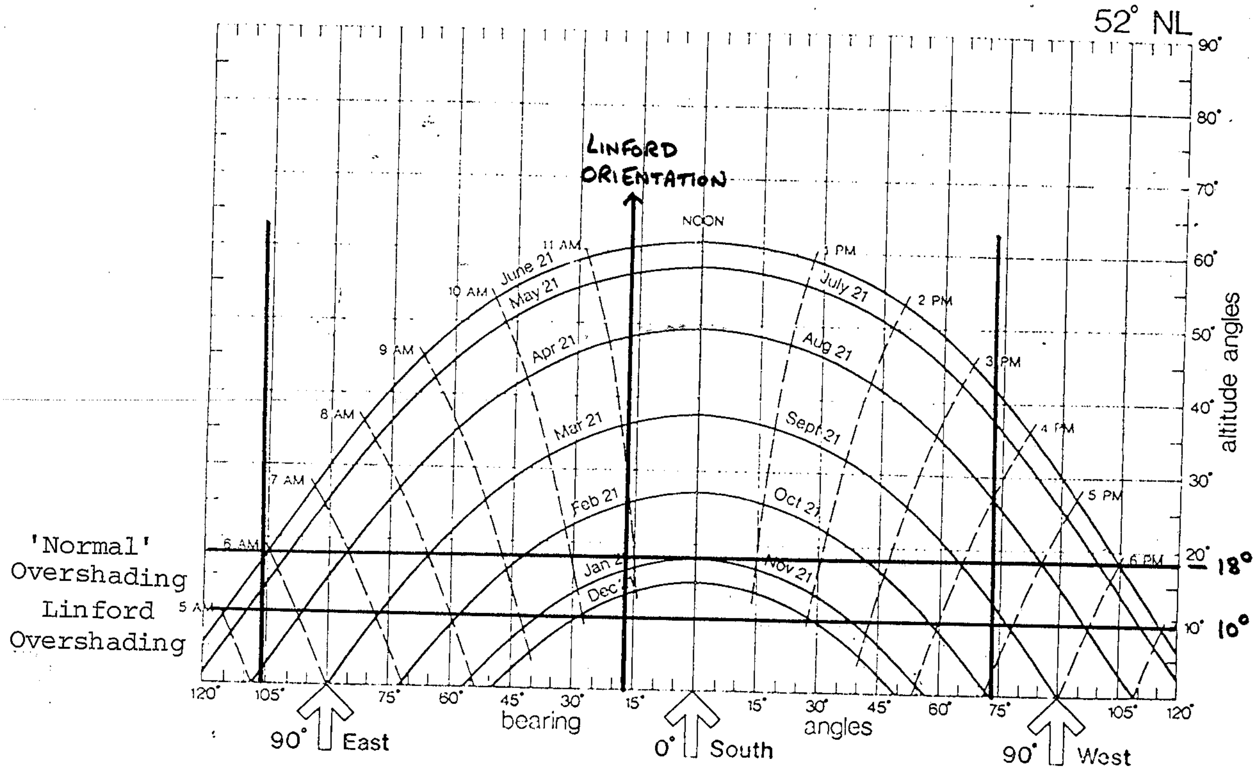



Figure 10.33 Choice of Overshading

Table 10.5 Overshading by Building Type and Age - Cambridge Survey

Average Percentages of received solar radiation* per type of dwelling and age group

| Age Groups Groups | Ter. | Ter. end | Semi det. | Det. | Bung. | Fl< 5fl | Fl> 4fl | Maison. |
|---|---|---|---|---|---|---|---|---|
| Before 1900 | 84 | 86 | 64 | 51 | 100 | 93 | | |
| 1900-1919 | 87 | 92 | 90 | 93 | - | - | - | - |
| 1919-1939 | 93 | 95 | 92 | 81 | 100 | 100 | - | - |
| 1939-1963 | 94 | 95 | 95 | 88 | - | 96 | - | 99 |
| 1963-1969 | 92 | 93 | 91 | 86 | 96 | 96 | - | 78 |
| 1970- | 82 | 99 | 90 | 84 | 92 | 84 | 100 | - |
| Average | 88 | 93 | 92 | 81 | 96 | 94 | 100 | 86 |

*Received radiation = obstruction radiation/unobstructed radiation on South-facing surface, October - May

Source Penz, ref. 10.9

The solar absorption has been adjusted by including an extra shading factor in the model to reduce the solar input from an equivalent 13 m² of solar aperture down to 10 m² for a house with clear windows and 8 m² for one with net curtains.

10.6.3. 'Normal' overshading and orientation

Lacking a proper control group for the Linford experiment, it is a little difficult to define the 'non-solar' house, especially in terms of overshading. It has thus been necessary to refer to an outside survey of houses carried out by the Martin Centre on the Cambridge housing stock (Reference 10.9).

This survey was intended to evaluate the potential for retrofit passive solar measures, but is a good record of typical site conditions. It involved the analysis of hundreds of photographs taken from a height of 1.2 metres above ground in front of houses, showing the solar obstructions. The shading profiles of surrounding buildings and trees were turned into a figure for the percentage reduction in solar radiation over the assumed heating season of October to May.

Table 10.5 shows a breakdown of average solar transmission by age and type of dwelling. For new construction, we are obviously interested in the bottom line. This shows a widespread of values. Detached houses, in particular, are badly overshaded and become progressively more so with age. This is almost entirely due to the surroundings of mature trees and this is likely to be the eventual fate of the Linford houses. For houses with low levels of overshading, the obstructions are most likely to be other buildings.

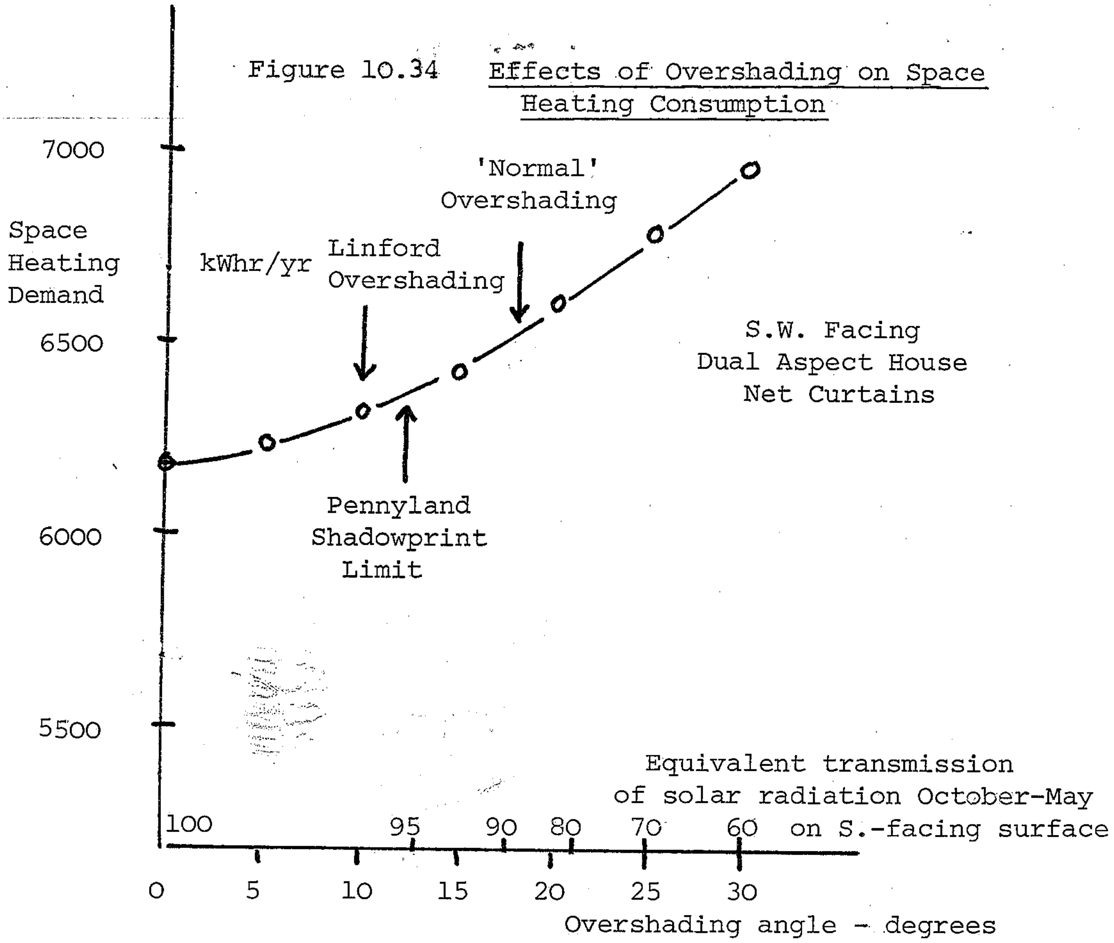
For the purposes of calculations, an average transmission of 90% has been taken. This corresponds to an overshading angle of 18°, i.e. the sun's direct rays are obstructed below a solar altitude of this much. As shown in Figure 10.33, these means that no direct solar rays will enter the ground floor windows over a period of two months in mid-winter.

The actual Linford overshading level was equivalent to an overshading angle of about 10° at the end of 1983, but will worsen slightly every year as the bushes to the south of the houses mature.

Also, for calculation purposes, it has been assumed that all the solar gains are effectively taken at ground floor window height and subject to overshading effects. Obviously solar gains to upstairs windows would not be so badly obstructed, but it is not really clear what the relative usefulness of upstairs solar gains are to downstairs ones. This is an area where modelling of a more complex nature would be useful.

The importance of overshading on house energy consumption can be seen in Figure 10.34, showing the calculated space heating demand of a south-west facing dual aspect house as a function of overshading angle and consequent percentage solar transmission. The precise definition of 'normal' overshading is thus quite important in making comparisons. One of the conclusions of the Cambridge survey was that overshading did not seem to be as bad as was originally thought and the overshading angle of 18° taken for this project is somewhat less than the figure of 25° taken in the original design calculations shown in Chapter 2.

Figure 10.34 Effects of Overshading on Space Heating Consumption



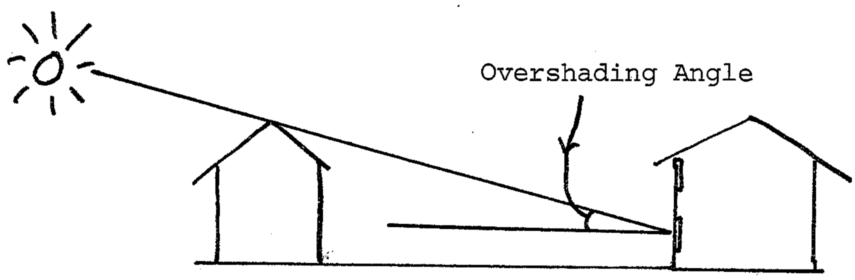
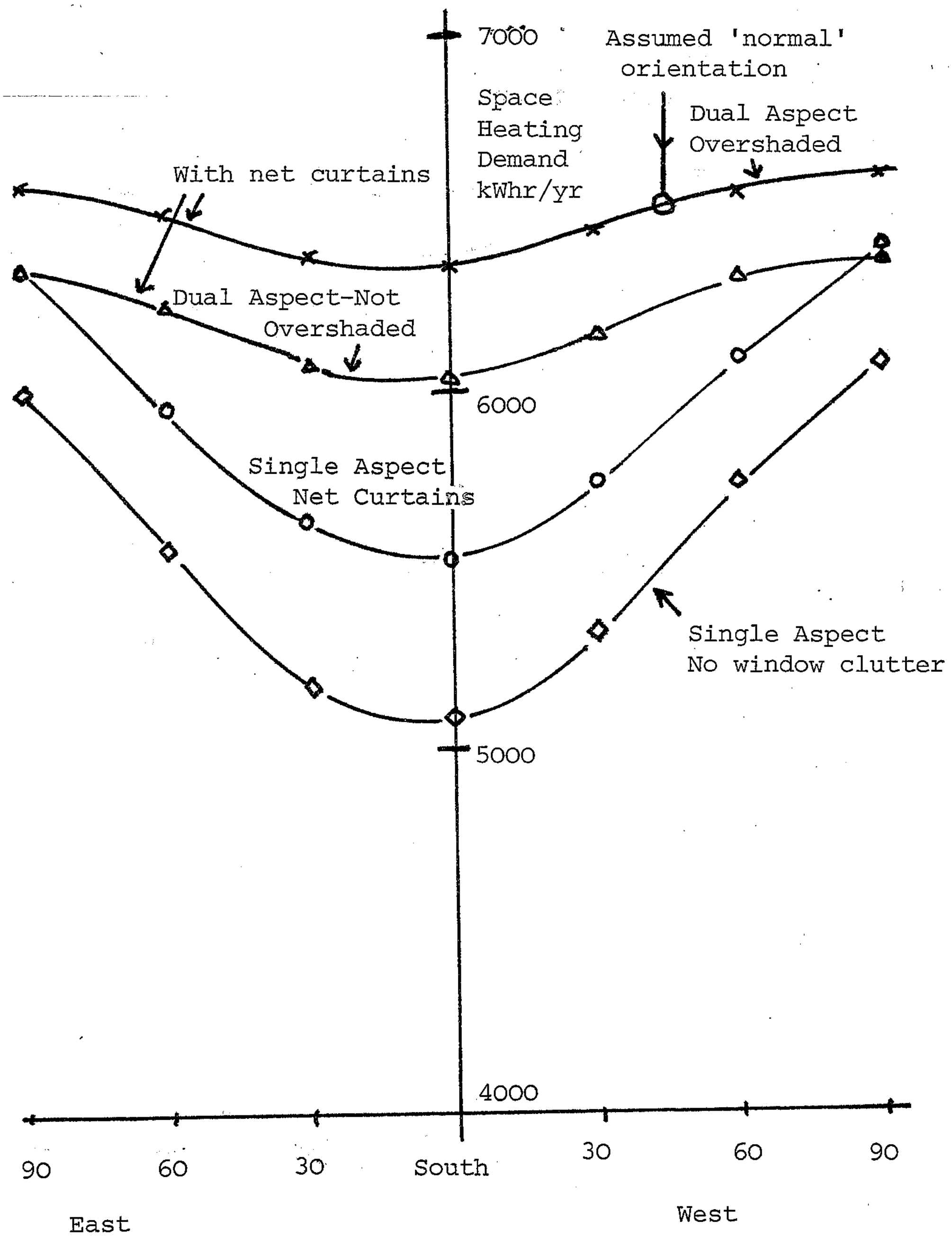



Figure 10.35 Effects of Orientation on Space Heating Demand



Defining a 'normal' house orientation for calculations is somewhat simpler. Fortunately the calculated variation of house space heating with orientation for an overshaded dual aspect house is fairly small, as shown in Figure 10.35. Thus for modelling purposes south-west has been taken as 'normal' orientation.

The actual Linford orientation of 20° east of south has been taken as 'south' for calculations.

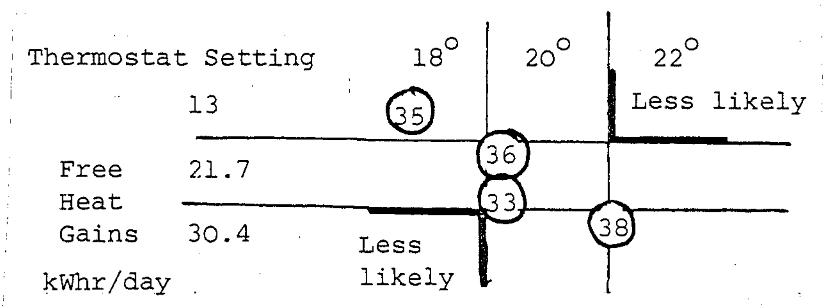
### 10.6.4. Comparison matrices

Having specified a house model and the overshading and orientation parameters, it is necessary to consider occupancy behaviour. As noted from the chapters dealing with the occupied houses, there is a wide range of life styles, leading to a widespread in annual energy consumptions. In order to get realistic estimates of marginal passive solar gains it is necessary to make comparisons over a similar wide range of occupancy assumptions, centred on the average observed figures.

The annual space heating consumptions of the house variants have thus been calculated for nine possible combinations of three whole-house thermostat settings, 18°, 20° and 22°C, and three values for free heat gains from cooking, lights, etc. These have been set to 21.7 kWh/day and varied ±40%. Single period heating of 16 hours/day has been assumed and this leads to average seasonal house temperatures about 0.5°C less than the thermostat settings. The weather data used has been Kew 1969, in common with the other NBSLD calculations.

These nine combinations have been arranged as a matrix for simplicity and the approximate positions of the four occupied houses analysed in detail are shown in Figure 10.36:-

Figure 10.36 Comparison Matrix and Typical House Performances



Unfortunately this positioning is not a perfect guide to the comparitive performances of the houses, since house 38 appears to have a higher heat loss and thus a higher space heating consumption than the others.

Temperature data from houses 39 and 40 has also been used in choosing the central thermostat setting of 20°C.

Overshading and orientation effects

Table 10.6 gives the annual space heating matrices for three basic house variants, all assumed to have normal window clutter, i.e. full net curtains. To the right are three comparison matrices showing the energy differences between each of the annual totals.

The three comparisons relate to the following changes in house condition:

| | |
|---|---|
| Difference 2-1 | Avoid overshading and using correct orientation. |
| Difference 3-2 | Concentrating the glazing on the south side of the house without changing the total area. |
| Difference 3-1 | The sum of the two above. |

The spread of space heating consumptions across each matrix is enormous, typically 3:1. The spread across the comparison matrix is slightly smaller, about 2:1. In practice, it would seem that of the nine combinations in the matrix, two are less likely to happen, high temperatures and low free heat gains and low temperatures with high free heat gains. By ignoring the two extremes, the spread in marginal gain values is considerably reduced.

We can thus conclude that without changing the normal degree of window clutter, it is possible to save approximately 930 ± 200 kWh/yr of useful space heating energy. It should be stressed that this calculation has been carried out strictly on an energy saved basis and that no credit has been given for the slightly higher seasonal average temperatures in the more 'solar' variants.

Reduction of window clutter

There are further possible reductions in energy consumption by removing the net curtains, thus increasing the assumed house solar aperture from 8 $m^2$ to 10 $m^2$. Again these possible gains have been expressed as the difference of two matrices for a south-facing single aspect house. These are shown in Table 10.7.

From this we would conclude that this increase in solar transmission is worth about 450 ± 150 kWh/yr.

Overall savings

As noted in Section 10.4, observations of window clutter on the Pennyland estate show an almost universal use of net curtains and hence the 'normal' level of window clutter for these calculations has been taken as being equivalent to full net curtains. The overall marginal gains for the Linford estate should thus also assume a 'normal' level of window clutter and be taken as 930 ± 200 kWh/yr from Table 10.6. Actual observations show a less than 'normal' use of net curtains at Linford, which may be due to the fact that the houses are not overlooked from the south side.

TABLE 10.6. SPACE HEATING DEMAND MATRICES

EFFECTS OF OVERSHADING AND ORIENTATION

1. DUAL ASPECT OVERSHADED S.W. FACING

| Thermostat Setting / Free Heat kWhr/day | 18° | 20° | 22° |
|---|---|---|---|
| 13 | 6366 | 8428 | 10956 |
| 21.7 | 4752 | 6497 | 8620 |
| 30.4 | 3408 | 4875 | 6681 |

DIFFERENCE 2 - 1

| | 18° | 20° | 22° |
|---|---|---|---|
| 13 | 462 | 522 | 584 |
| 21.7 | 431 | 456 | 563 |
| 30.4 | 383 | 445 | 515 |

2. DUAL ASPECT NON-OVERSHADED S.FACING

| Thermostat Setting / Free Heat kWhr/day | 18° | 20° | 22° |
|---|---|---|---|
| 13 | 5904 | 7906 | 10372 |
| 21.7 | 4321 | 6041 | 8057 |
| 30.4 | 3025 | 4430 | 6166 |

DIFFERENCE 3 - 2

| | 18° | 20° | 22° |
|---|---|---|---|
| 13 | 452 | 587 | 705 |
| 21.7 | 357 | 472 | 574 |
| 30.4 | 278 | 377 | 450 |

3. SINGLE ASPECT NON-OVERSHADED

| Thermostat Setting / Free Heat kWhr/day | 18° | 20° | 22° |
|---|---|---|---|
| 13 | 5452 | 7319 | 9667 |
| 21.7 | 3964 | 5569 | 7483 |
| 30.4 | 2747 | 4053 | 5716 |

DIFFERENCE 3 - 1

| | 18° | 20° | 22° |
|---|---|---|---|
| 13 | 914 | 1109 | 1289 |
| 21.7 | 788 | 928 | 1137 |
| 30.4 | 661 | 822 | 965 |

## COMPARISON MATRIX - REDUCING WINDOW CLUTTER

### 4. SINGLE ASPECT HOUSE WITH NET CURTAINS  R = 8 $m^2$

| Thermostat Setting | 18° | 20° | 22° |
|---|---|---|---|
| 13 | 5452 | 7319 | 9667 |
| Free Heat 21.7 | 3964 | 5569 | 7483 |
| kWhr/day 30.4 | 2747 | 4053 | 5716 |

### DIFFERENCE

| Thermostat Setting | 18° | 20° | 22° |
|---|---|---|---|
| 13 | 440 | 582 | 702 |
| Free Heat 21.7 | 316 | 451 | 532 |
| kWhr/day 30.4 | 251 | 323 | 409 |

### 5. SINGLE ASPECT HOUSE NO CURTAINS  R = 10 $m^2$

| Thermostat Setting | 18° | 20° | 22° |
|---|---|---|---|
| 13 | 5012 | 6737 | 8965 |
| Free Heat 21.7 | 3648 | 5118 | 6951 |
| kWhr/day 30.4 | 2496 | 3730 | 5307 |

### OVERALL DIFFERENCE 5 - 1

| Thermostat Setting | 18° | 20° | 22° |
|---|---|---|---|
| 13 | 1354 | 1691 | 1991 |
| Free Heat 21.7 | 1104 | 1379 | 1669 |
| kWhr/day 30.4 | 912 | 1145 | 1374 |

Figure 10.37 Effect of Length of Heating Season on Marginal Passive Gains

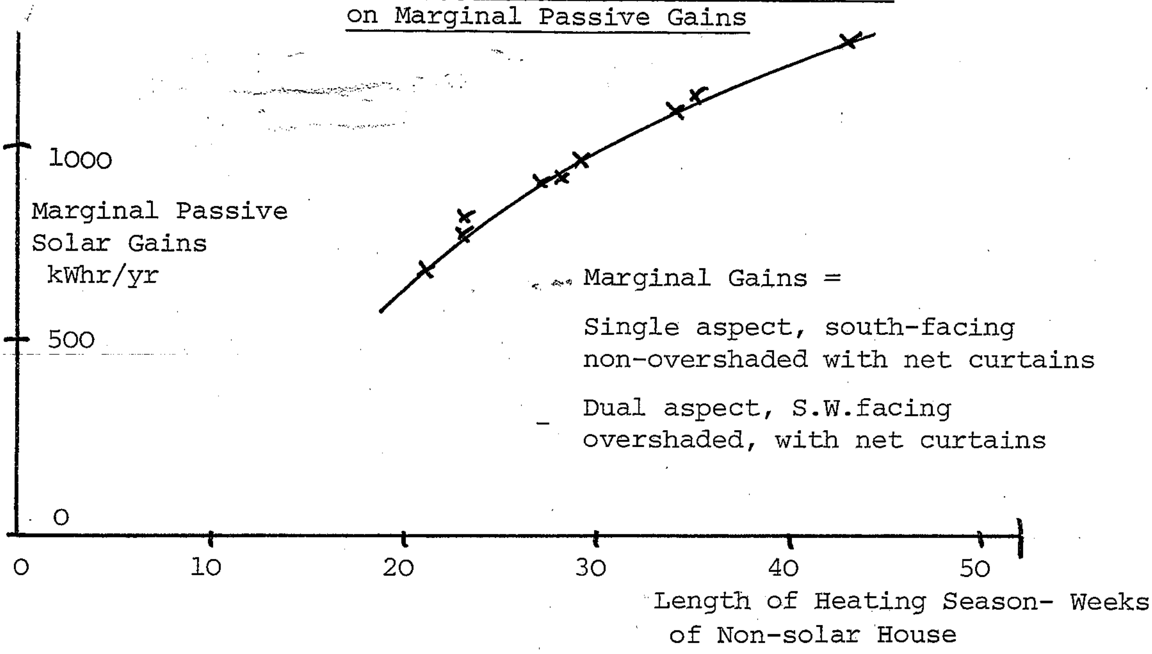



Figure 10.38 Effect of Available Solar Radiation on Marginal Gains

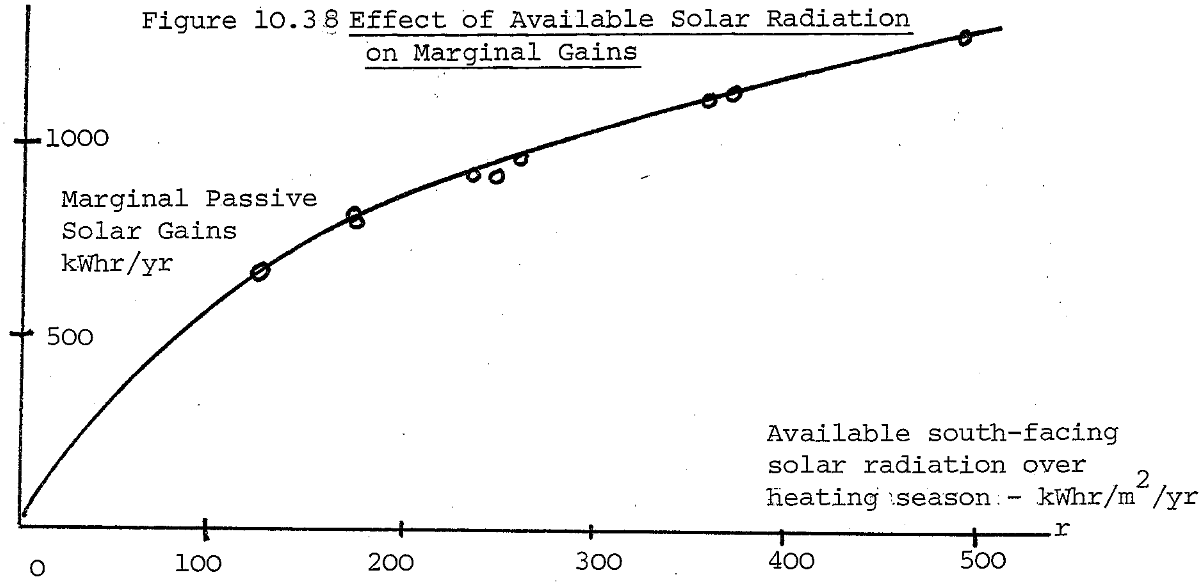
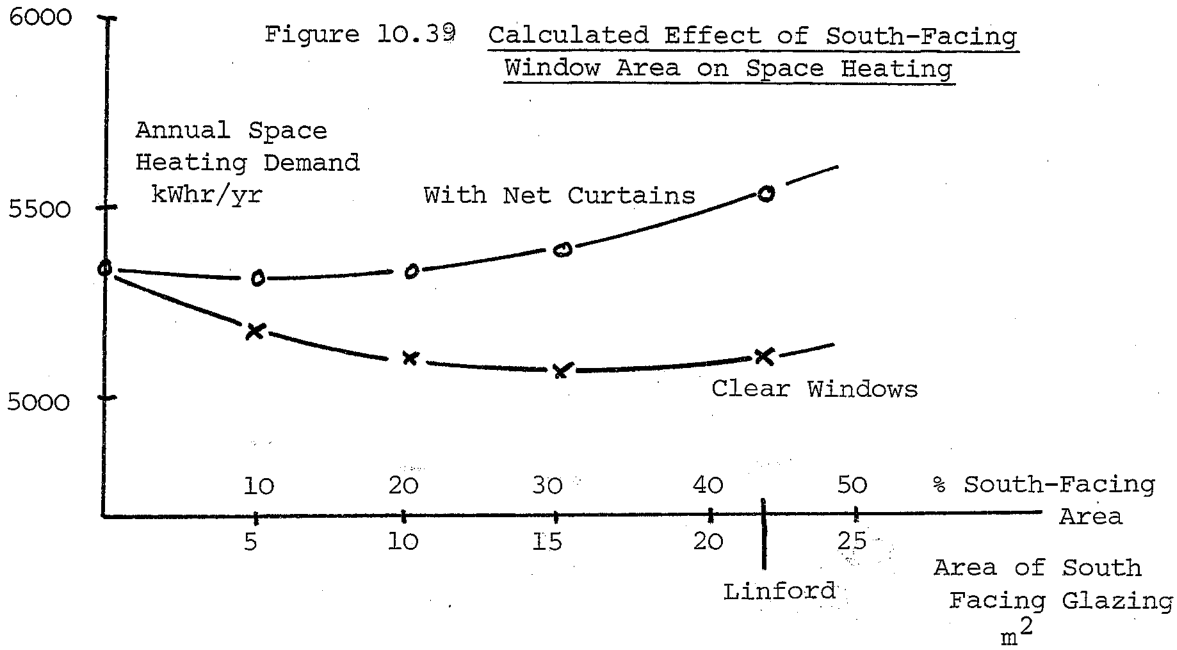



Figure 10.39 Calculated Effect of South-Facing Window Area on Space Heating



For houses without net curtains or appreciable window clutter the marginal gains have been calculated at 1380 ± 300 kWh/yr. Given that of the four houses for which solar apertures have been estimated, two had full net curtains and solar apertures of around 8 m² and two had clear windows and demonstrably higher solar apertures, an estate average marginal gain figure of 1150 ± 250 kWh/yr seems reasonable.

Obviously this is an area where the interaction between privacy considerations and levels of curtaining require further research.

### 10.6.5. Marginal gains and heating season length

It is difficult to know quite how to summarise the relation of marginal gains to internal temperatures and free heat gains. One way that seems to have some physical explanation is to relate them to the length, and consequently the amount of solar radiation during, the heating season.

Figure 10.37 shows the marginal passive solar gains of a Linford house with full net curtains as a function of the length of the heating season. For this purpose the 'heating season' has been defined on a weekly basis as those weeks where the average space heating demand of the 'non-solar' house is greater than 5 kWh/day.

Figure 10.38 shows the same thing expressed in terms of incident south-facing solar radiation over a heating season. Obviously the more solar radiation there is in the heating season, the better in terms of energy savings, a 'solar' house is likely to perform. Further work suggests that this relation of marginal gains to heating season length also extends to the effects of house insulation, as well as internal temperatures and free heat gains.

One conclusion from these plots is that passive solar techniques are not likely to be of much use in 'super-insulated' houses (i.e. better insulation levels than Linford). Such houses are likely to have a very small heating season, mainly consisting of the dull mid-winter months of December to February when there is little solar radiation available to use. For most of the time they would be almost entirely heated by free heat gains from cooking, etc. This is, of course, not to say that there are other aesthetic and psychological reasons for having some mid-winter sunshine in the house.

Conversely, passive solar gains are likely to be most useful in larger, poorly insulated houses, possibly the more up-market ones, where full central heating and a high house floor area per occupant would lead to a long heating season. Such houses would also be good candidates for further insulation improvements. This trade-off between extra insulation and passive solar design can only be resolved by further design and costing work.

### 10.6.6. Optimum window area

Much design work is done on the basis that passive solar heating is a method of energy generation akin to active solar or any other kind of heating. Figures of up to 100 kWh/m²yr have been quoted for the energy generation of a south-facing window operating in the 'thermal diode' mode, i.e. being automatically insulated when less energy flows in than out. Hence there is a design pressure to increase windows towards 100% south-facing glazing.

The more normal behaviour regarding windows exhibited in this and the Pennyland project has in practice involved restricting the flow of solar energy into the house during the day with net curtains and half-drawn blinds and restricting the heat losses at night with curtains of an unknown, but probably reasonable, thermal efficiency.

Figure 10.39 shows the calculated space heating demand of a Linford house with 'average' occupancy behaviour, as a function of south-facing window area for two conditions, one with net curtains and the other with clear windows. This graph is plotted to the same vertical scale as Figure 10.35 showing the effects of house orientation.

The basic conclusion from this plot is that south-facing window area is not a matter of great thermal importance up to about 40% south-facing area. The optimum window area for space heating is about 15 m² for clear windows and about 5 m² with net curtains, but the optima are very flat. It is more likely that cost and aesthetic reasons would determine the actual area put on a house.

As far as Building Regulations go, it is obviously desirable to restrict the area and U-value of north-facing glazing. For the Linford houses every extra square metre of north-facing glazing increases the heat demand by about 80 kWh/yr. It is not desirable to restrict the south-facing glazing in the same manner, since the window energy balance is approximately zero, rather than being strongly negative. How such a formula might be worded is, of course, a matter of conjecture.

## 10.7. Conclusions

A major objective of this project has been to assess the impact of direct passive solar gains on the use of energy in these houses. The results of this investigation may be summarised as follows:-

1. The Linford houses have worked well as direct gain passive solar houses.

2. The experiment allowed the solar gains to be expressed as being equivalent to a clear south-facing solar aperture. This solar aperture is less than the total southerly glazing area of 16.5 m² and takes into account the transmission through the glazing, and any window clutter, such as curtains and the absorption at the internal surfaces of the house.

3. The test house measurements give an equivalent solar aperture of 10 m² ± 1 m² for unobstructed windows and 8 m² ± 1 m² for full net curtains.

4. Measurements in the occupied houses reinforce these estimates of solar aperture, with values of between 6.8 and 10.7 m².

5. For a solar aperture of 10 $m^2$ the absolute solar contribution would be 2500-4500 kWh/yr, depending on the assumed length of the heating season. This figure compares well with similar estimates obtained from simple energy balances in four occupied houses. The average absolute solar contribution in the four houses was 3573 kWh/yr which is equivalent to 24% of the gross heating requirement or about two-thirds of the net space heating consumption of 5748 kWh/yr. (See Chapter 12.)

6. Estimates have been made of the marginal solar energy saving which results from the passive solar measures. This has been done by comparing computer models of the houses and 'normal' randomly orientated, overshaded, dual aspect houses with net curtains. A typical Linford house has the potential to save around 1400 kWh/yr of useful space heating energy over the normal house given unobstructed windows. The solar savings are dependent on internal temperature and incidental gains and could be larger if higher temperatures are assumed thereby extending the heating season.

7. Of the 1400 kWh/yr, about a third is due to correct orientation and avoiding overshading, one third is due to concentrating the glazing on the south side and the remaining third is due to avoiding net curtains and window clutter.

8. The solar apertures were less than the expected value of 13 $m^2$ for clear unobstructed glazing which was used in initial computer modelling. This could be due to the following reasons:-

   (a) over-optimistic values for the absorptivity of rooms in the model.

   (b) overshading by the roof eaves and window reveals.

   (c) over-estimates of the usefulness of solar gains upstairs and

   (d) a problem of definition of external air temperature under conditions of high solar fluxes.

9. The concrete ground floor slab cannot be considered as 'primary thermal mass'. In practice carpets isolate the floor slab from solar gains with as little as 15% of incident radiation on the floor being transferred to the storage.

10. It was found that insulating the floor slab did not decrease the apparent solar aperture.

## References

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10.2 C.Uglow — Calculation of Energy Use in Dwellings, Building Science Research and Technology, Vol 11, No.1.,1981.

10.3 P. Basnett — 'Estimation of Solar Radiation Falling on Vertical Surfaces from Measurements in the Horizontal Plane', E.C.R.C., September 1975.

10.4 A. Dupagne, H. Heikhaus, J. Lebrun, J.Uyttenbroek — 'Practical Method to Evaluate the Effect of Building Characteristics in the Energy Needs for Heating', Lab. de Physique du Batiment, University of Liege, 1979.

10.5. J. Siviour — 'Experiment Thermal Calibration of Houses, Comparitive Instrumentation of Low Energy Houses', Colloquium, University of Liege, 1981.

10.6. B. Ford — 'Thermal Performance Monitoring of a Terrace House with Conservatory', Dept. Design Research, Royal College of Art, 1982.

10.7. W Shurcliff — 'Shocking Questions about Solar Heating, Home Remedies', Proceedings 1st National Retrofit Conference, Princeton, 1980.

## Appendix 10.1. Calculation Errors in NBSLD

During the course of the design and experimental work two program errors in the published NBSLD program have been detected.

The first is a relatively minor error concerning the calculation of the time of sunset. The relevant line in the subroutine 'SUN' should read:

```
S(12) = 24.-S(11) - 2*S(29)
```

instead of:

```
S(12) = 24.-S(11).
```

This error has no serious effect on the energy calculations for this project.

The more serious error concerns the termination of the routine 'RESPTK' in finding the X, Y and Z response functions. Beyond a certain point in these functions, they can be assumed to be exponential in form (see Figure A.10.1). The error seems to involve the decision as to whether or not the three functions have reached the exponential stage during the calculation process, this involving the successive estimation of terms of the series.

The routine tests whether it has reached the exponential tail by generating an error function, TEST3, and seeing whether it is small. The test is carried out on the series ZRK(1,N) which eventually becomes the X series:

```
TEST1 = ZRK(1,N)/ZRK(1,N-1)
TEST2 = ZRK(1,N-1)/ZRK(1,N-2)
TEST3 = ABS(TEST1 - TEST2)
IF(TEST3-0.00001)59,59,58
```

i.e. if TEST3 $<$ 0.00001 then the tail is exponential from then on. The above is taken from an obviously early version of NBSLD published in 'Dynamic Thermal Performance of an Experimental Masonry Building', N.B.S. Building Science Series 45. In later versions of the program, as documented in NBSLD, N.B.S. Building Sceince Series 69, in both its 1976 and 78 revisions, the last line reads,

```
IF(TEST3-0.001)59,58,59
```

i.e. TEST3 is increased by two orders of magnitude. This means that the exponential tail is assumed to be reached earlier, presumably to save on computing time.

The problem is that it is the X series that is tested and this tends to reach an exponential tail before the Y series. This results in possible serious errors in the calculation of the Y series and in particular that

$$\sum_{j=1}^{\infty} Y_j \neq U$$

This can really upset heat loss calculations. This is most marked on highly insulated heavyweight structures where the X and Y series are both small numbers, varying slowly.

For the case of the Linford house walls with 100 mm insulation

$$\sum_{j=1}^{\infty} Y_j = 0.6\ U \text{ instead of } U$$

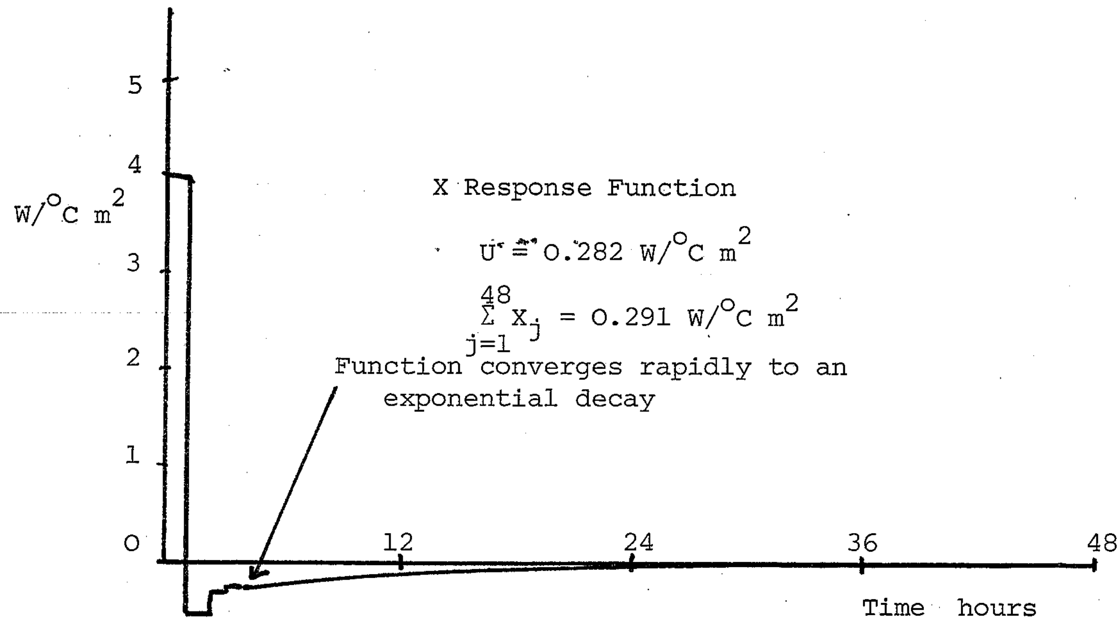
Curiously the problem should be even worse in U.S. units of B.T.U./ft² °F, where the numbers are even smaller.

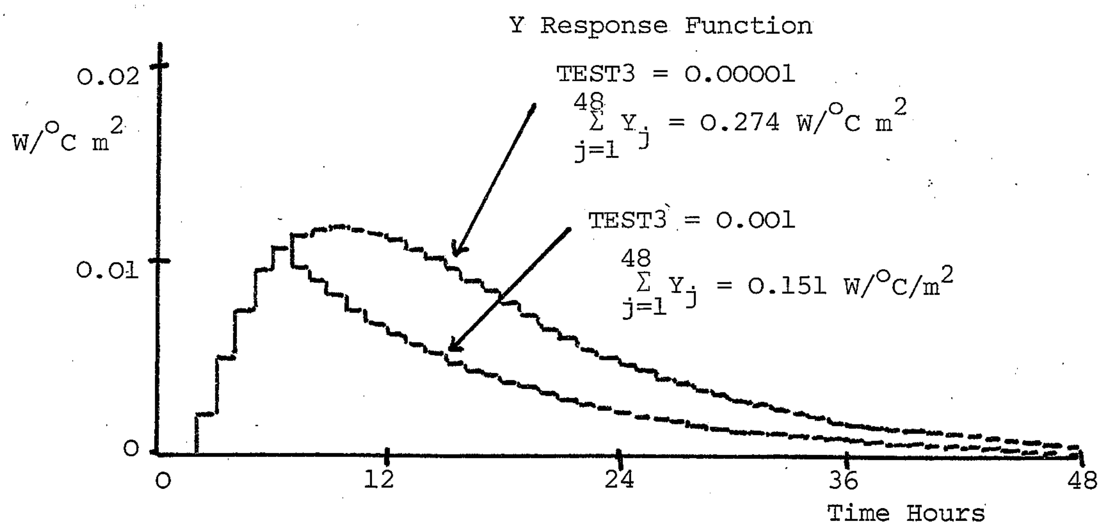
Although this program error does not significantly effect the simulation program used for Pennyland and Linford, because traps were inserted in the program to make sure that

$$\sum_{j=1}^{\infty} X_j = \sum_{j=1}^{\infty} Y_j = U$$

it could easily be present in programs developed from NBSLD, such as BLAST, BUILD, and TAS, though they may use a finite difference technique to generate the response functions rather than the Laplace transform method of NBSLD.

Figure A.10.1. X & Y RESPONSE FUNCTIONS OF LINFORD EXTERNAL WALL




Construction :- Inside Surface Resistance
Plaster
100 mm Dense Concrete
100 mm Insulation
100 mm Brick
Outside Surface Resistance

Appendix 10.2 Solar Storage and the X-Response Function

The small rise and fall in an otherwise constant internal temperature produced by the effects of solar radiation is very similar to the unit temperature impulse used to define the X response function in response factor modelling. It is thus fairly easy to make statements about the energy flow consequences of these small temperature 'blips' both as regards individual building elements such as the floor and walls and, in theory at least, about the whole house.

The X response function for a piece of building fabric is a way of expressing the apparent thermal mass as well as the U-value. It is defined as the response in energy flow at the inside surface to a unit triangular temperature impulse of, in this case, one degree-hour, i.e. the internal temperature is raised by one degree for one hour. A typical response function for a wall surface is shown in figure A 10.2.1. This shows a rapid flow of heat into the wall as the temperature rises, followed by a long return flow after the temperature has fallen again.

If the piece of building fabric is external, more heat will flow into the surface than flows out again, the difference being the U-value:-

$$\sum_{j=1}^{\infty} X_j = U$$

These X response functions can be added together like U-values to give a whole house X response function which reflects the total house thermal mass and heat loss. This must also include the X response functions of the internal walls and an allowance for furniture. This response of the whole house to a unit temperature impulse is shown in figure A 10.2.2. This is similar in form to that of the wall, but obviously much larger in value. Given that for this whole house X-response function

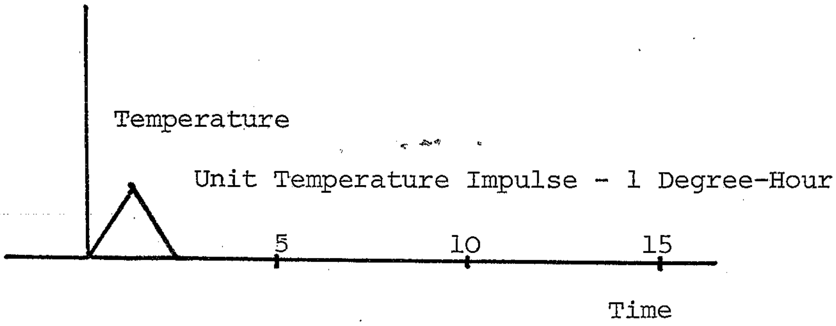
$$\sum_{j=1}^{\infty} X_j = \Sigma\, U.A + C_V$$

we can immediately estimate the ratio of energy put into storage in the building fabric as a result of the temperature impulse, i.e. $X_1$ to that lost permanently out through the building heat losses $\Sigma\, U.A + C_V$. Given a value of $X_1$ of 2280 W/$^{\circ}$C and $\Sigma\, U.A + C_V$ = 215 W/$^{\circ}$C, it is clear that at least ten times more energy goes into storage than is lost, i.e. the storage efficiency is better than 90%.

The rate at which the stored energy reemerges is relatively slow, only 50% has reappeared to displace space heating energy after five hours and 10% remaining after 22 hours.

Larger and longer temperature impulses are simply calculated by summing the effects of unit impulses by linear superposition, so this does not affect the basic conclusions.

Obviously this is a very crude model and neglects the true multi-room nature if the house, but it does give a fair insight into the general nature of heat flows.



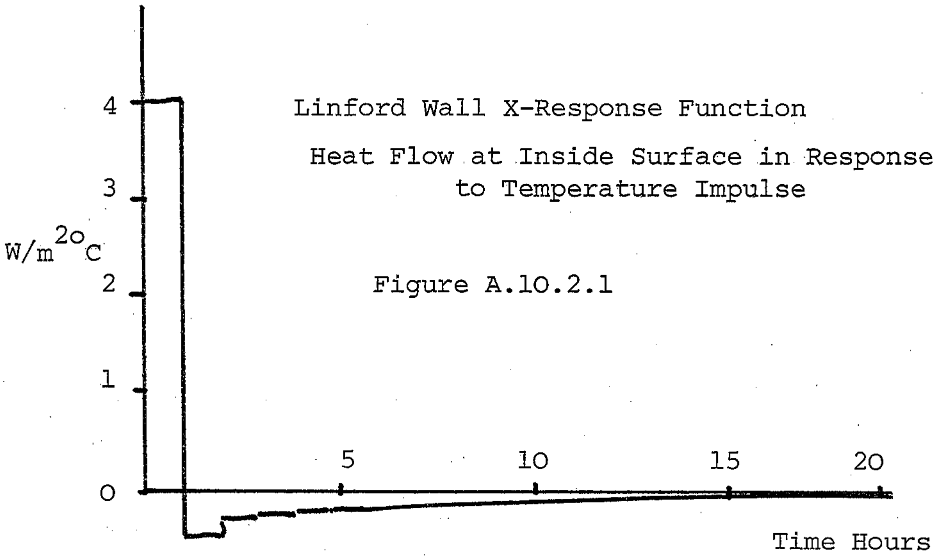




Figure A.10.2.1

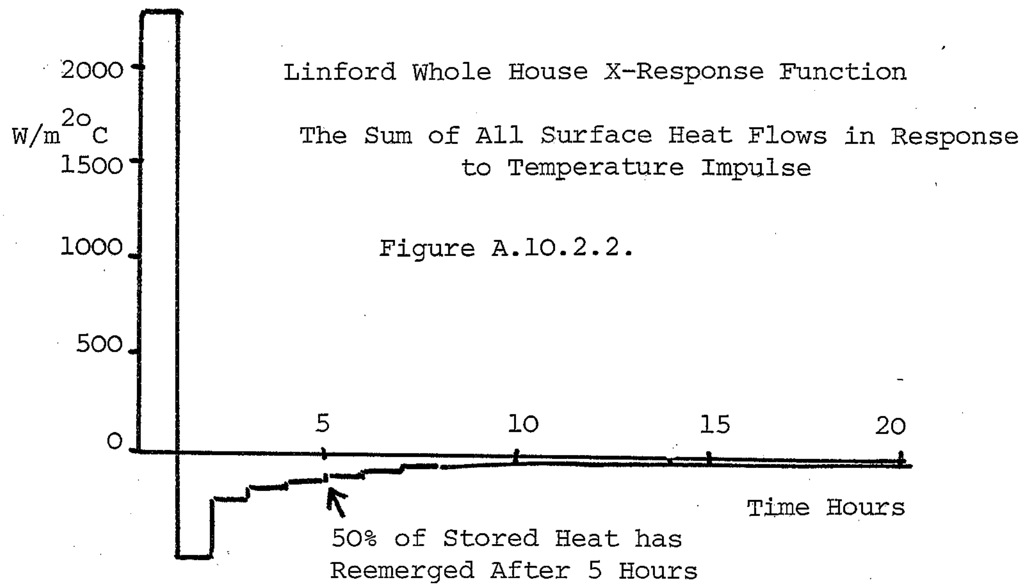



Figure A.10.2.2.

## Appendix 10.3 Air Temperatures and High Solar Flux

The modelling of house energy use has assumed that heat is lost to the external air temperature, $T_a$, though no allowance has been made for the effects of solar radiation on the external wall and roof surfaces. The air temperature which has been used for thermal calibration purposes has been measured inside a Stevenson screen. This is essentially a white-painted box fitted with louvred sides (see monitoring section). The problem is the degree to which this arrangement actually measures trueair temperature on sunny days, and the resulting errors that this may cause in determining the solar aperture.

For crude calculation purposes we can assume that the box is made of some perfectly conducting substance so that at any time it has the same temperature all over. We can also assume it to be a 1 metre cube, for simplicity. If we work on a daily average basis and take a typical spring day with a daily total of south-facing solar radiation of 1 $kWhr/m^2$, then the radiation on the top, east and west faces will also be approximately 1 $kWhr/m^2$. The radiation on the north face will be about 0.4 $kWhr/m^2$. Assuming a solar absorptivity of 50%, this gives a daily total solar absorption of 4.4 x 0.5 = 2.2 kWhr.

This absorbed solar radiation will raise the daily average box temperature above the true air temperature $T_a$ by an error amount $e_1$. The energy will be conducted back to the external air through surface resistances assumed to be 0.055 $m^2{}^oC/W$ on the outside of the box and 0.13 $m^2{}^oC/W$ on the inside.

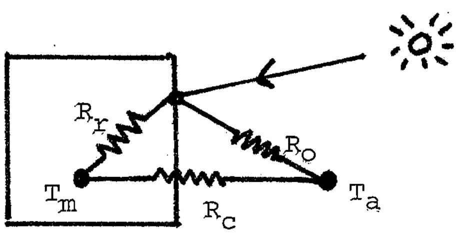
$$\text{Solar Absorbed} = \text{Heat Lost to Air Outside Box} + \text{Heat Lost to Air Inside Box}$$

$$\frac{2.2 \times 1000}{24} = \frac{e_1 \times 6}{0.055} + \frac{e_1 \times 6}{0.13}$$

$$e_1 = 0.59\ ^oC$$

i.e. the daily average screen temperature is raised by 0.59$^o$C for every $kWhr/m^2$ day of south-facing solar radiation.

The actual temperature sensor is mounted inside the box. It is coupled to the box temperature by a radiation resistance and by a convection resistance to the internal air, assumed to be at the same temperature as the external air.




Assuming a high surface emmisivity of 0.9 and a value of the radiation coefficient $h_r$ of 5.1 $W/m^2{}^oC$ gives the radiation resistance $R_r$ = 0.22 $m^2{}^oC/W$.

The convection resistance $R_c$ has been taken as 0.13 $m^{2o}C/W$, assuming an internal air movement of 0.5 m/sec. The average measured air temperature $T_m$ would thus lie somewhere between the true air temperature $T_a$ and the box surface temperature $T_a + e_1$. If $T_m = T_a + e_2$ then:-

$$e_2 = e_1 \cdot \frac{R_c}{R_r + R_c} = 0.59 \cdot \frac{0.13}{0.35}$$

$$e_2 = 0.22^{o}C$$

Thus for every kWhr/$m^2$day of south-facing solar radiation, the average daily temperature is in error by 0.22$^o$C.

While this is not very important for most purposes it can have an effect on the determination of the solar aperture by regression.

If we take the house heat balance equation:-

$$Q + K = ( \Sigma U.A + C_v).( T_{in} - T_a) - R.S$$

and substitute for $T_a$ the measured air temperature $T_m = T_a + e_2.S$ :-

$$Q + K = ( \Sigma U.A + C_v).( T_{in} - T_m + e_2.S ) - R.S$$

$$= ( \Sigma U.A + C_v).( T_{in} - T_m ) - ( R - e_2.( \Sigma U.A + C_v)).S$$

We are thus likely to get a regression with the same value of house heat loss, but with a smaller solar aperture, the reduction being dependent on the magnitude of the heat loss. For the Linford houses with a total heat loss of about 5 kWhr/$^o$C day this apparent reduction in solar aperture amounts to:-

$$e_2 \cdot ( \Sigma U.A + C_v ) = 0.22 \times 5 = 1.1 \ m^2$$

This may go some way in explaining the discrepancy between the calculated solar aperture with clear windows of 13 $m^2$ and the measured value of 10 $m^2$.

This calculation is obviously very crude and the answers will vary enormously with wind speed. The basic tendency for the solar aperture to be cancelled out in proportion to the house heat loss has a curious consequence. It may mean that for a house with a high heat loss and a small window area it will be impossible to detect any response to solar radiation for the simple reason that the Stevenson screen is a better passive solar collector than the house.

It may be necessary in future passive solar projects to make sure that an aspirated air temperature sensor is used, although this will then no longer be a true 'meteorological' parameter.

Night sky radiation effects may slightly offset this solar problem, since sunny days are likely to have cloudless nights during which the radiation temperature will be less than the air temperature. Initial calculations suggest that these effects are at least a factor of three smaller than the basic solar effect.

# 11. INCIDENTAL GAINS

CONTENTS



This chapter gives detailed estimates of the incidental heat gains in the occupied houses, from sources such as cooking, electrical appliances, occupancy gains etc. Although this was done primarily to enable estimates to be made of the thermal and passive solar performance of the occupied houses, the data in itself provides a useful source on incidental heat gains in low energy houses.

# 11. INCIDENTAL GAINS

## 11.1 Introduction

Certain day-to-day activities carried out by the occupants around the house produce appreciable amounts of heat, some of which is useful in reducing the amount of heat required from the space heating system. These "incidental" or "free" heat gains originate from a number of sources e.g.:

Occupants' body heat
Lighting and electrical appliances
Cooking (gas or electricity)
Hot water use and cylinder losses
Boiler casing losses

It is a matter of argument as to just how much of these heat gains are useful in reducing space heating requirements, as some may be produced at times when heating is not required, and the distribution around the house is not uniform - for example, a large proportion of the total may originate in the kitchen and bathroom. Furthermore, in these rooms odours and water vapour tend to accompany the heat gains, and the occupants may increase the ventilation thereby reducing their potential heating benefit.

It is the purpose of this section to describe how the incidental heat gains were estimated along with the assumptions used, and present data for four houses showing a range of hourly, daily, monthly and seasonal patterns. This data has been used to assist other forms of analysis, e.g. correlation of energy consumption with $\Delta T$ and solar radiation (Chapter 10) and energy balances (Chapter 12).

## 11.2 Methods of estimation

The following sub-sections describe how the absolute energy inputs from the various sources were estimated or measured, without making any further specific assumptions about their usefulness or otherwise in reducing space heating requirement. This is because the data is used elsewhere in this report for "energy accounting" purposes, where attempts are made to identify all the various energy inputs and outputs.

### 11.2.1 Occupants' body heat

Heat inputs from the occupants themselves were calculated assuming emissions of:

| | |
|---|---|
| Adult | 80 W daytime |
| | 60 W night-time |
| Child | 60 W daytime |
| | 40 W night-time |

(Reference 11.1)

## Tables 11.1a-d Occupancy heat gains

| HOUR | UNITS = WATTS | | | |
|---|---|---|---|---|
| | MAN | WOMAN | 2 CHILDREN | |
| 0 | 60 | 60 | 60 | 60 |
| 1 | 60 | 60 | 60 | 60 |
| 2 | 60 | 60 | 60 | 60 |
| 3 | 60 | 60 | 60 | 60 |
| 4 | 60 | 60 | 60 | 60 |
| 5 | 60 | 60 | 60 | 60 |
| 6 | 60 | 60 | 60 | 60 |
| 7 | 60 | 60 | 60 | 60 |
| 8 | 0 | 80 | 80 | 80 |
| 9 | 0 | 80 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 |
| 11 | 0 | 80 | 0 | 0 |
| 12 | 0 | 80 | 0 | 0 |
| 13 | 0 | 80 | 0 | 0 |
| 14 | 0 | 80 | 0 | 0 |
| 15 | 0 | 80 | 0 | 0 |
| 16 | 80 | 80 | 0 | 0 |
| 17 | 80 | 80 | 80 | 80 |
| 18 | 80 | 80 | 80 | 80 |
| 19 | 80 | 80 | 80 | 80 |
| 20 | 80 | 80 | 80 | 80 |
| 21 | 80 | 80 | 80 | 80 |
| 22 | 80 | 80 | 80 | 80 |
| 23 | 80 | 80 | 60 | 60 |
| | TOTAL = 5.0 KWH/DAY | | | |

Table 11.1a Occupancy gains assumed for house 33

| HOUR | UNITS = WATTS | | |
|---|---|---|---|
| | MAN | WOMAN | CHILD |
| 0 | 60 | 60 | 40 |
| 1 | 60 | 60 | 40 |
| 2 | 60 | 60 | 40 |
| 3 | 60 | 60 | 40 |
| 4 | 60 | 60 | 40 |
| 5 | 60 | 60 | 40 |
| 6 | 60 | 60 | 40 |
| 7 | 60 | 60 | 40 |
| 8 | 0 | 80 | 60 |
| 9 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 |
| 13 | 0 | 0 | 0 |
| 14 | 0 | 0 | 0 |
| 15 | 0 | 80 | 60 |
| 16 | 80 | 80 | 60 |
| 17 | 80 | 80 | 60 |
| 18 | 80 | 80 | 40 |
| 19 | 80 | 80 | 40 |
| 20 | 80 | 80 | 40 |
| 21 | 80 | 80 | 40 |
| 22 | 80 | 80 | 40 |
| 23 | 80 | 80 | 40 |
| | TOTAL = 3.2 KWH/DAY | | |

Table 11.1b Occupancy gains assumed for house 35

| HOUR | UNITS = WATTS | |
|---|---|---|
| | MAN | WOMAN |
| 0 | 60 | 60 |
| 1 | 60 | 60 |
| 2 | 60 | 60 |
| 3 | 60 | 60 |
| 4 | 60 | 60 |
| 5 | 60 | 60 |
| 6 | 60 | 60 |
| 7 | 60 | 60 |
| 8 | 80 | 80 |
| 9 | 0 | 0 |
| 10 | 80 | 0 |
| 11 | 0 | 0 |
| 12 | 80 | 0 |
| 13 | 0 | 0 |
| 14 | 80 | 0 |
| 15 | 0 | 80 |
| 16 | 80 | 80 |
| 17 | 80 | 80 |
| 18 | 80 | 80 |
| 19 | 80 | 80 |
| 20 | 80 | 80 |
| 21 | 80 | 80 |
| 22 | 80 | 80 |
| 23 | 80 | 80 |
| TOTAL = 2.7 KWH/DAY | | |

Table 11.1c Occupancy gains assumed for house 36

| HOUR | UNITS = WATTS | | |
|---|---|---|---|
| | MAN | WOMAN | CHILD |
| 0 | 60 | 60 | 40 |
| 1 | 60 | 60 | 40 |
| 2 | 60 | 60 | 40 |
| 3 | 60 | 60 | 40 |
| 4 | 60 | 60 | 40 |
| 5 | 60 | 60 | 40 |
| 6 | 60 | 60 | 40 |
| 7 | 60 | 60 | 40 |
| 8 | 0 | 80 | 60 |
| 9 | 0 | 80 | 60 |
| 10 | 0 | 80 | 60 |
| 11 | 0 | 80 | 60 |
| 12 | 0 | 80 | 60 |
| 13 | 0 | 80 | 60 |
| 14 | 0 | 80 | 60 |
| 15 | 0 | 80 | 60 |
| 16 | 80 | 80 | 60 |
| 17 | 80 | 80 | 60 |
| 18 | 80 | 80 | 40 |
| 19 | 80 | 80 | 40 |
| 20 | 80 | 80 | 40 |
| 21 | 80 | 80 | 40 |
| 22 | 80 | 80 | 40 |
| 23 | 80 | 80 | 40 |
| | TOTAL = 4.0 KWH/DAY | | |

Table 11.1d Occupancy gains assumed for house 38

After discussions with each household, the following occupancy patterns were assumed:

| House | Occupants | Occupancy notes |
|---|---|---|
| 33 | 2 adults<br>2 teenage children | House occupied by 1 adult during day |
| 35 | 2 adults<br>1 small child | House unoccupied between approximately 9 a.m. and 3 p.m. |
| 36 | 2 adults | House intermittently occupied during day by 1 adult |
| 38 | 2 adults<br>1 small child | House occupied by 1 adult and child during day |

From interviews with each household, detailed occupancy profiles were drawn up. The occupancy gains schedules are given in Tables 11.1a-1d. For house 33, the heat emissions for the two teenage children were taken as that for adults.

The resulting daily heat inputs from the occupants ranges from 2.7 kWh/day (2 adults) to 5.0 kWh/day (2 adults + 2 teenage children).

### 11.2.2 Appliance and cooking electricity

Total electricity consumption was measured on an hourly basis, and was all assumed as heat input to the houses. Three out of the four houses considered used electric cookers, and this was measured separately, in addition to total consumption; thus appliance electricity could be identified as the difference between the two.

For the one house with gas cooking, the appliance electricity was simply equal to the total electricity.

### 11.2.3 Cooking gas

This was measured on an hourly basis using a modified standard domestic gas meter (see Chapter 17).

### 11.2.4 Hot water gains

Heat gains from hot water use occur in two ways - standing losses from the hot water storage cylinder, and cooling of water in baths and sinks etc. before being drained away.

The heat loss rate from hot water cylinders has been estimated from measurements in the test house, when the cylinder was maintained at 50°C over a period of several weeks, with no draw-off of hot water.

The measurement was 1.31 kWh/day for a storage temperature of 50°C and an average internal air temperature of 25$^{o}$C. This is equivalent to a heat loss rate of 0.0524 kWh/day$^{o}$C (temperature difference between tank and house).

However, the time clock was set for 1 hour only during the morning, thus the average storage temperature is likely to have been several degrees cooler. Assuming an effective average storage temperature of 45$^{o}$C, the heat loss rate becomes 0.0655 kWh/day$^{o}$C.

For the occupied houses, thermostat settings were 65$^{o}$C (from interviews). Using the seasonal average whole house temperatures for each house (Chapter 13), heat losses were estimated as follows:

| | | | |
|---|---|---|---|
| House | 33 | 2.97 | kWh/day |
| " | 35 | 3.23 | " |
| " | 36 | 3.04 | " |
| " | 38 | 2.94 | " |
| Average | | 3.05 | " |

A figure of 3.0 kWh/day was taken for each house, for simplicity. This compares with 2.9 kWh/day measured at the Bradville Solar House (Reference 11.2) and 2.6 kWh/day reported by Wozniak (Reference 11.3). The latter figure is for a storage temperature of 60$^{o}$C and would increase to 2.9 kWh/day for a temperature of 65$^{o}$C (assuming an average house temperature of 20$^{o}$C).

Heat gains from hot water use have been estimated as:

$$G_{water} = 0.2 \times (Q_{water} - Q_{cyl})$$

where $Q_{water}$ = energy delivered to hot water cylinder (measured by heat meter)

$Q_{cyl}$ = cylinder losses (above)

i.e. 20% of the energy input in raising the volume of hot water used from the cold feed temperature to the final storage temperature.

This estimate is made in the absence of any direct reference, but some indirect comparisons can be made with other published estimates:

e.g. house 33

The measured energy delivered to the hot water cylinder for 212 days from October to April was 2602 kWh.

Of this 212 X 3 kWh/day = 636 kWh are estimated as standing losses from the cylinder.

The gains from hot water use, $Q_{water} = 0.2 \times (2602-636) = 393$ kWh

Thus the total hot water gains = 636+393 = 1029 kWh = 4.9 kWh/day

This compares with 4.3 kWh/day <u>useful</u> gains estimated by Siviour (Reference 11.1), which would be equivalent to a <u>total</u> input of 5.4 kWh/day assuming a usefulness factor of 0.8.

Uglow (Reference 11.4) reports a minimum of 2.9 kWh/day useful gains from a survey of field trials, equivalent to 3.6 kWh/day total heat input assuming a usefulness factor of 0.8.

### 11.2.5 Boiler casing losses

The balanced-flue gas boiler is wall-mounted in the kitchen, and there will be some heat input other than that delivered to the radiators (measured by heat meters) due to heat emission from the casing when the boiler is operating.

No reference can be found to quantify this heat loss, and a figure of 5% of the total gas burned by the boiler has been used. Private communication with British Gas suggests that this is a reasonable assumption.

Heat losses from the pipes between radiators is already included in the heat meter measurements due to the positioning of the instrumentation.

### 11.2.6 Total incidental gains

Thus the expression used to estimate the daily total heat input to the house in kWh/day from the various sources listed above is:

$$I_g = O_g + E_t + [3.0+0.2(Q_{water}-3.0)] + 0.05G_b \quad [+G_c]$$

| Total heat gains | Occupancy gains | Total electricity consumption | Hot water gains | Boiler casing losses | Gas cooking (where used) |
|---|---|---|---|---|---|

## 11.3 Hourly profiles

Average hourly profiles for the various components of the incidental gains over the heating season (October-April) are given in Tables 11.2a-c and Figure 11.1. These have been calculated by, for example averaging all the 8 a.m. values, all the 9 a.m. values and so on, to build an average hourly profile. Three houses are shown, all with electric cookers; it was not possible for house 38 (which has a gas cooker), as the pulse generator on the gas cooking meter failed, leaving only weekly data available.

Although magnitudes are different, the general pattern is similar in each case, and to be expected - a "baseload" of about 0.3-0.5 kW, with strong peaks at breakfast-time and evening. The peaks are due to increases in electricity use (cooking, lighting etc.) and hot water use, and increased use of the heating system giving rise to larger boiler casing heat losses. During the evening, the sum of the incidental gains can be a substantial part of the gross heating requirement. For house 33, the average over the evening period is about 1.5 kW, peaking at over 2 kW. For a 19°C inside-outside temperature difference, 1.5 kW incidental gains represents about one-third of the gross requirement.

Tables 11.2a-c Average hourly incidental gains, October 1982-April 1983

| HOUR | BODY HEAT | HOT WATER GAINS | BOILER CASING LOSSES | TOTAL ELEC. | TOTAL |
|---|---|---|---|---|---|
| | UNITS = kWh | | | | |
| 0 | 0.240 | 0.125 | 0.031 | 0.267 | 0.663 |
| 1 | 0.240 | 0.125 | 0.013 | 0.191 | 0.569 |
| 2 | 0.240 | 0.125 | 0.009 | 0.169 | 0.543 |
| 3 | 0.240 | 0.125 | 0.010 | 0.158 | 0.533 |
| 4 | 0.240 | 0.125 | 0.009 | 0.163 | 0.537 |
| 5 | 0.240 | 0.125 | 0.010 | 0.161 | 0.536 |
| 6 | 0.240 | 0.125 | 0.010 | 0.207 | 0.582 |
| 7 | 0.240 | 0.173 | 0.064 | 0.322 | 0.799 |
| 8 | 0.240 | 0.225 | 0.101 | 0.405 | 0.971 |
| 9 | 0.080 | 0.435 | 0.178 | 0.467 | 1.160 |
| 10 | 0.000 | 0.227 | 0.080 | 0.432 | 0.739 |
| 11 | 0.080 | 0.179 | 0.062 | 0.423 | 0.744 |
| 12 | 0.080 | 0.208 | 0.098 | 0.566 | 0.952 |
| 13 | 0.080 | 0.224 | 0.125 | 0.482 | 0.911 |
| 14 | 0.080 | 0.224 | 0.148 | 0.323 | 0.775 |
| 15 | 0.080 | 0.216 | 0.176 | 0.429 | 0.901 |
| 16 | 0.160 | 0.220 | 0.195 | 0.882 | 1.457 |
| 17 | 0.320 | 0.287 | 0.228 | 1.242 | 2.077 |
| 18 | 0.320 | 0.305 | 0.224 | 0.898 | 1.747 |
| 19 | 0.320 | 0.347 | 0.248 | 0.752 | 1.667 |
| 20 | 0.320 | 0.309 | 0.237 | 0.677 | 1.543 |
| 21 | 0.320 | 0.269 | 0.215 | 0.633 | 1.437 |
| 22 | 0.320 | 0.170 | 0.183 | 0.554 | 1.227 |
| 23 | 0.280 | 0.127 | 0.126 | 0.424 | 0.957 |
| | 5.000 | 5.020 | 2.780 | 11.227 | 24.027 |

Table 11.2a Average hourly incidental gains ( Oct - Apr )

House 33

| HOUR | BODY HEAT | HOT WATER GAINS | BOILER CASING LOSSES | TOTAL ELEC. | TOTAL |
|---|---|---|---|---|---|
| | UNITS = kWh | | | | |
| 0 | 0.160 | 0.125 | 0.007 | 0.105 | 0.397 |
| 1 | 0.160 | 0.125 | 0.007 | 0.111 | 0.403 |
| 2 | 0.160 | 0.125 | 0.007 | 0.127 | 0.419 |
| 3 | 0.160 | 0.125 | 0.008 | 0.129 | 0.422 |
| 4 | 0.160 | 0.125 | 0.007 | 0.121 | 0.413 |
| 5 | 0.160 | 0.125 | 0.007 | 0.116 | 0.408 |
| 6 | 0.160 | 0.190 | 0.096 | 0.144 | 0.590 |
| 7 | 0.160 | 0.337 | 0.329 | 0.316 | 1.142 |
| 8 | 0.140 | 0.207 | 0.181 | 0.360 | 0.888 |
| 9 | 0.000 | 0.149 | 0.097 | 0.291 | 0.537 |
| 10 | 0.000 | 0.155 | 0.081 | 0.236 | 0.472 |
| 11 | 0.000 | 0.146 | 0.068 | 0.242 | 0.456 |
| 12 | 0.000 | 0.185 | 0.075 | 0.369 | 0.629 |
| 13 | 0.000 | 0.182 | 0.072 | 0.268 | 0.522 |
| 14 | 0.000 | 0.156 | 0.066 | 0.240 | 0.462 |
| 15 | 0.140 | 0.128 | 0.063 | 0.240 | 0.571 |
| 16 | 0.220 | 0.156 | 0.086 | 0.370 | 0.832 |
| 17 | 0.220 | 0.175 | 0.109 | 0.584 | 1.088 |
| 18 | 0.200 | 0.191 | 0.109 | 0.722 | 1.222 |
| 19 | 0.200 | 0.172 | 0.102 | 0.578 | 1.052 |
| 20 | 0.200 | 0.156 | 0.092 | 0.443 | 0.891 |
| 21 | 0.200 | 0.125 | 0.074 | 0.437 | 0.836 |
| 22 | 0.200 | 0.125 | 0.031 | 0.232 | 0.588 |
| 23 | 0.200 | 0.125 | 0.007 | 0.129 | 0.461 |
| | 3.200 | 3.810 | 1.781 | 6.910 | 15.701 |

Table 11.2b Average hourly incidental gains ( Oct - Apr )

House 35

| HOUR | BODY HEAT | HOT WATER GAINS | BOILER CASING LOSSES | TOTAL ELEC. | TOTAL |
|---|---|---|---|---|---|
| | UNITS = kWh | | | | |
| 0 | 0.120 | 0.125 | 0.011 | 0.267 | 0.523 |
| 1 | 0.120 | 0.125 | 0.009 | 0.262 | 0.516 |
| 2 | 0.120 | 0.125 | 0.009 | 0.254 | 0.508 |
| 3 | 0.120 | 0.125 | 0.010 | 0.259 | 0.514 |
| 4 | 0.120 | 0.125 | 0.009 | 0.256 | 0.510 |
| 5 | 0.120 | 0.125 | 0.035 | 0.266 | 0.546 |
| 6 | 0.120 | 0.224 | 0.142 | 0.328 | 0.814 |
| 7 | 0.120 | 0.336 | 0.368 | 0.443 | 1.267 |
| 8 | 0.160 | 0.150 | 0.077 | 0.342 | 0.729 |
| 9 | 0.000 | 0.136 | 0.061 | 0.351 | 0.548 |
| 10 | 0.080 | 0.136 | 0.055 | 0.353 | 0.624 |
| 11 | 0.000 | 0.156 | 0.056 | 0.362 | 0.574 |
| 12 | 0.080 | 0.157 | 0.060 | 0.387 | 0.684 |
| 13 | 0.000 | 0.146 | 0.056 | 0.367 | 0.569 |
| 14 | 0.080 | 0.146 | 0.075 | 0.315 | 0.616 |
| 15 | 0.080 | 0.135 | 0.088 | 0.329 | 0.632 |
| 16 | 0.160 | 0.254 | 0.151 | 0.382 | 0.947 |
| 17 | 0.160 | 0.315 | 0.285 | 0.551 | 1.311 |
| 18 | 0.160 | 0.144 | 0.198 | 0.625 | 1.127 |
| 19 | 0.160 | 0.135 | 0.199 | 0.508 | 1.002 |
| 20 | 0.160 | 0.154 | 0.199 | 0.528 | 1.041 |
| 21 | 0.160 | 0.195 | 0.147 | 0.524 | 1.026 |
| 22 | 0.160 | 0.125 | 0.028 | 0.387 | 0.700 |
| 23 | 0.160 | 0.125 | 0.014 | 0.289 | 0.588 |
| | 2.720 | 3.919 | 2.342 | 8.935 | 17.916 |

Table 11.2c Average hourly incidental gains ( Oct - Apr )

House 36

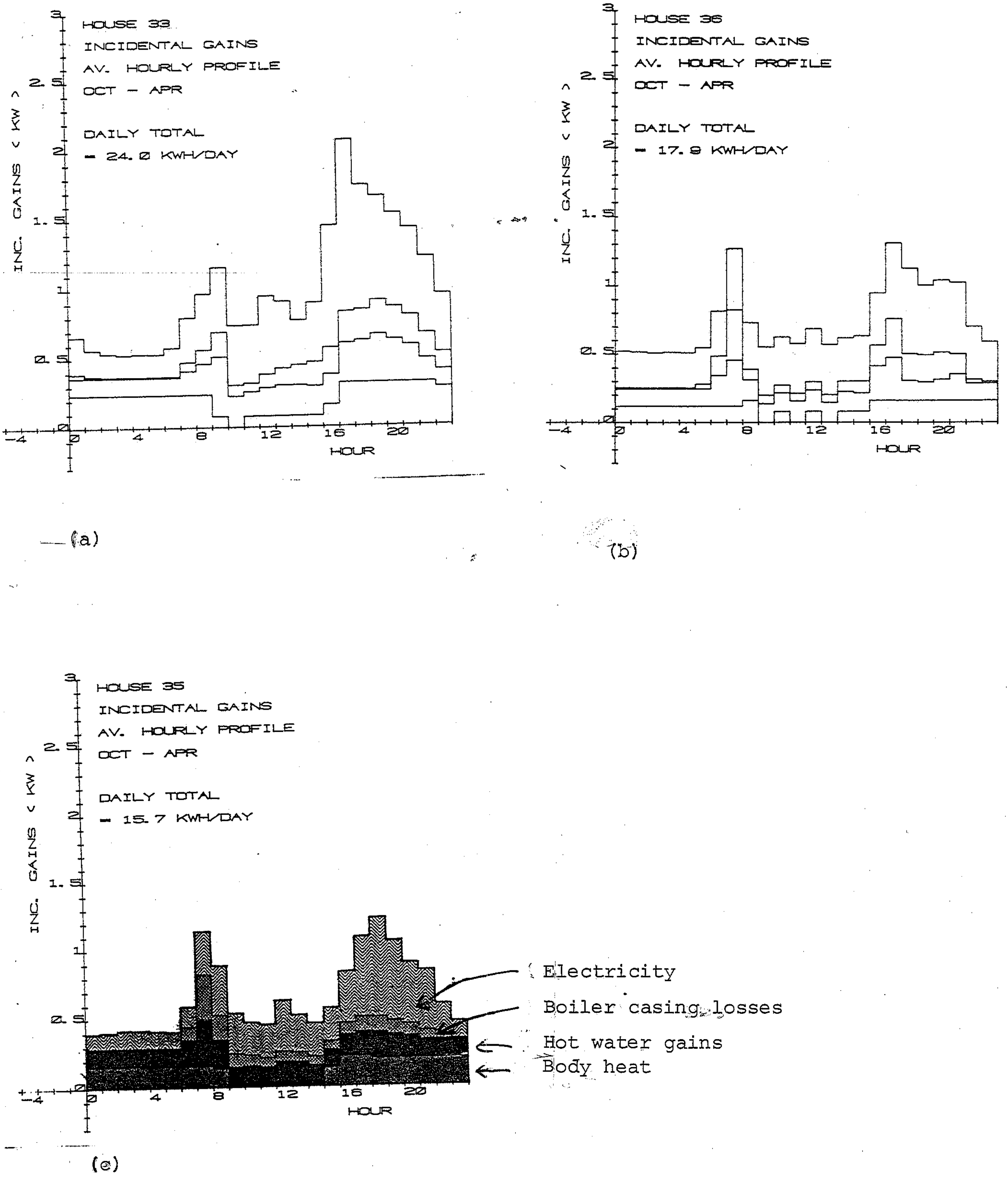



Figure 11.1 Average hourly profile of incidental heat gains October 1982-April 1983

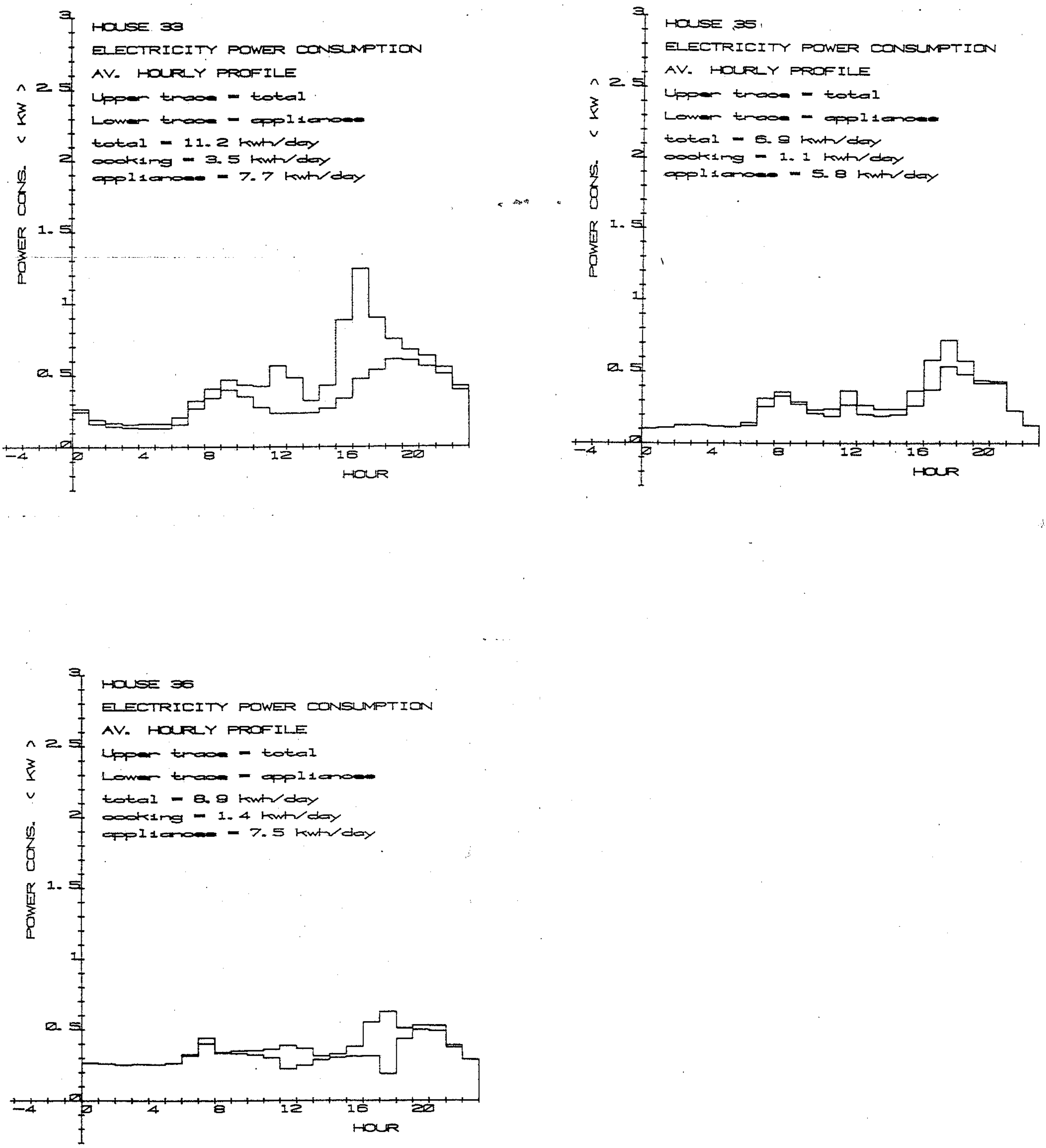



Figure 11.2 Hourly profiles of electricity consumption, showing cooking component

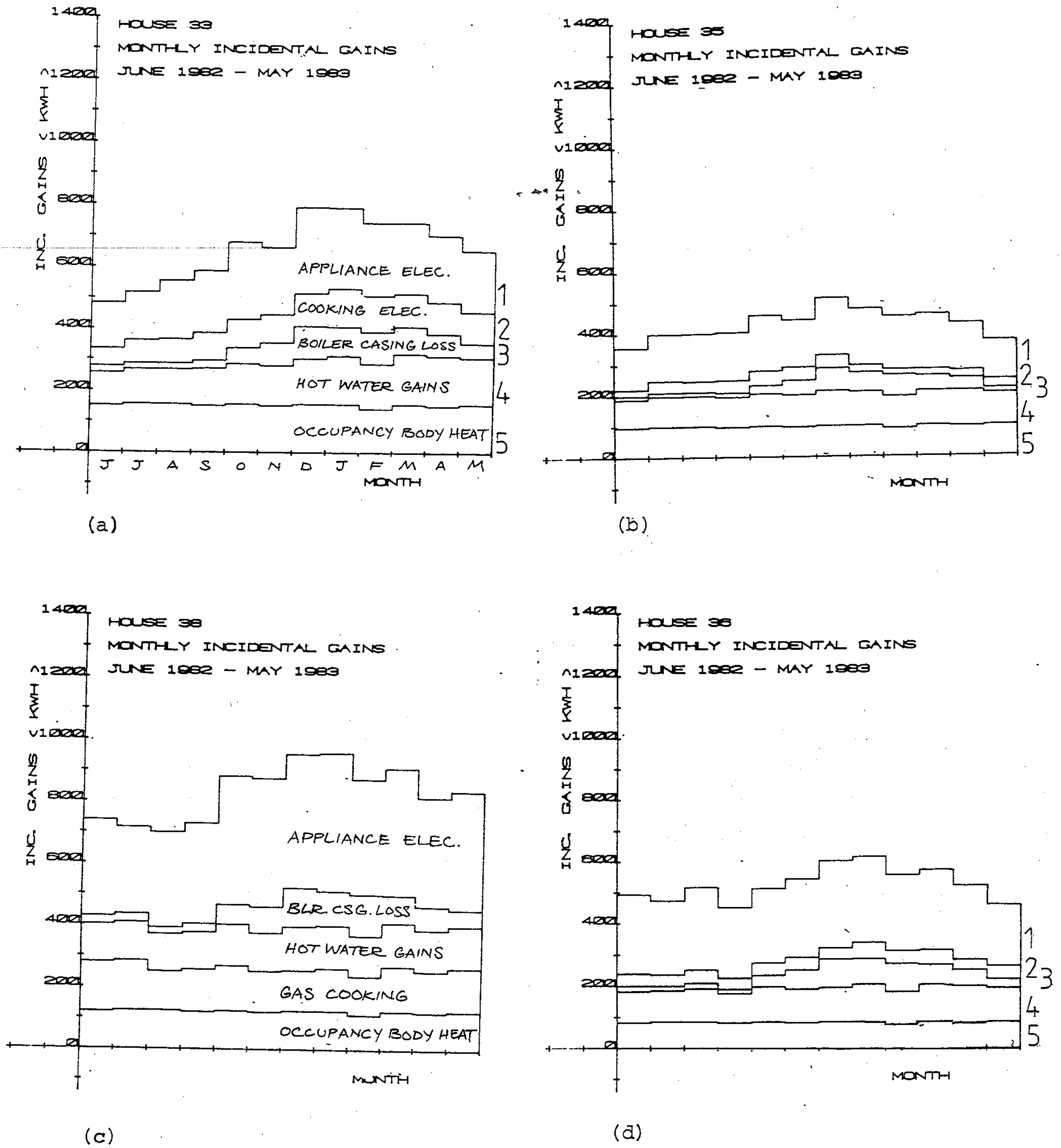



Figure 11 .3 Monthly incidental gains

Hourly profiles of electricity consumption only are shown in Figure 11.2 and Table 11.3a-c, showing the cooking and appliance consumptions separately. The 3.5 kWh/day cooking consumption in house 33 is over three times that of house 35 (there are two adults and two teenage children as opposed to two adults and one small child), and forms 30% of the total of 11.4 kWh/day. For house 35, the cooking consumption is only 1.1 kWh/day, and is only 16% of the total of 6.7 kWh/day.

## 11.4 Daily averages

Over the period October-April, the daily averages were:

| | | |
|---|---|---|
| House 33 | 24.0 | kWh/day |
| " 35 | 15.7 | " |
| " 36 | 17.9 | " |
| " 38 | 29.5 | " |
| Average | 21.7 | " |

The component breakdown of the average is as follows:

| | kWh/day | |
|---|---|---|
| Occupants | 3.7 | 17% |
| Hot water | 4.1 | 19% |
| Boiler casing | 2.5 | 12% |
| Electrical appliances | 8.8 | 40% |
| Cooking | 2.6 | 12% |

It can be seen that electrical appliances contribute more than twice as much as any other source.

## 11.5 Monthly and seasonal totals

Monthly data is given in Tables 11.4a-d and Figure 11.3.

All components except body heat show slight seasonal variations.

The cooking electricity consumption of house 35 falls sharply from January 1983 onwards, although the total remains approximately the same. This was due to the introduction of a micro-wave oven, the consumption of which registered as an appliance.

For house 38, the electricity estimates given are slightly lower than the measured totals, to allow for the use of a tumble drier situated in the garage. It was assumed that it consumed 3 kWh/week between December and February, 2 kWh/week for November and March, and nothing for the other months.

## Tables 11.4a-d Monthly incidental heat gains

| MONTH | BODY HEAT | HOT WATER | BOILER CASING | ELECTRICITY COOK. | ELECTRICITY APP. | ELECTRICITY TOTAL | TOTAL |
|---|---|---|---|---|---|---|---|
| Jun 82 | 150 | 106 | 21 | 57 | 149 | 206 | 483 |
| Jul 82 | 155 | 111 | 19 | 76 | 156 | 232 | 517 |
| Aug 82 | 155 | 111 | 20 | 79 | 189 | 268 | 554 |
| Sep 82 | 150 | 119 | 25 | 91 | 200 | 291 | 586 |
| Oct 82 | 155 | 129 | 52 | 92 | 249 | 341 | 678 |
| Nov 82 | 150 | 128 | 74 | 92 | 216 | 308 | 661 |
| Dec 82 | 155 | 146 | 106 | 106 | 276 | 382 | 790 |
| Jan 83 | 155 | 155 | 94 | 124 | 258 | 382 | 787 |
| Feb 83 | 140 | 144 | 104 | 117 | 233 | 350 | 739 |
| Mar 83 | 155 | 163 | 88 | 107 | 227 | 334 | 740 |
| Apr 83 | 150 | 161 | 72 | 103 | 214 | 317 | 700 |
| May 83 | 155 | 151 | 46 | 102 | 198 | 300 | 652 |
| ANNUAL | 1825 | 1624 | 721 | 1146 | 2565 | 3711 | 7887 |
| WINTER | 1060 | 1026 | 590 | 741 | 1673 | 2414 | 5095 |
| SUMMER | 765 | 598 | 131 | 405 | 892 | 1297 | 2792 |

( winter = oct - apr, summer = may - sep )

Table 11.4a Monthly incidental gains in kWh - House 33

| MONTH | BODY HEAT | HOT WATER | BOILER CASING | ELECTRICITY COOK. | ELECTRICITY APP. | ELECTRICITY TOTAL | TOTAL |
|---|---|---|---|---|---|---|---|
| Jun 82 | 96 | 91 | 12 | 20 | 136 | 156 | 410 |
| Jul 82 | 99 | 98 | 13 | 38 | 152 | 190 | 456 |
| Aug 82 | 99 | 99 | 13 | 35 | 155 | 190 | 457 |
| Sep 82 | 96 | 98 | 14 | 40 | 156 | 196 | 458 |
| Oct 82 | 99 | 105 | 26 | 47 | 180 | 227 | 514 |
| Nov 82 | 96 | 104 | 46 | 43 | 153 | 196 | 497 |
| Dec 82 | 99 | 113 | 72 | 43 | 186 | 229 | 570 |
| Jan 83 | 99 | 110 | 61 | 23 | 184 | 207 | 534 |
| Feb 83 | 89 | 104 | 68 | 18 | 172 | 190 | 502 |
| Mar 83 | 99 | 112 | 47 | 22 | 178 | 200 | 515 |
| Apr 83 | 96 | 115 | 40 | 25 | 153 | 178 | 484 |
| May 83 | 99 | 103 | 15 | 29 | 126 | 155 | 429 |
| ANNUAL | 1166 | 1252 | 427 | 383 | 1931 | 2314 | 5169 |
| WINTER | 677 | 763 | 360 | 221 | 1206 | 1427 | 3234 |
| SUMMER | 489 | 489 | 67 | 162 | 725 | 887 | 1935 |

( winter = oct - apr, summer = may - sep )

Table 11.4b Monthly incidental gains in kWh - House 35

| MONTH | BODY HEAT | HOT WATER | BOILER CASING | ELECTRICITY COOK. | ELECTRICITY APP. | ELECTRICITY TOTAL | TOTAL |
|---|---|---|---|---|---|---|---|
| Jun 82 | 81 | 100 | 17 | 40 | 254 | 294 | 493 |
| Jul 82 | 83 | 100 | 14 | 37 | 237 | 274 | 473 |
| Aug 82 | 83 | 107 | 18 | 43 | 265 | 308 | 516 |
| Sep 82 | 81 | 94 | 13 | 36 | 227 | 263 | 451 |
| Oct 82 | 83 | 113 | 37 | 40 | 238 | 278 | 512 |
| Nov 82 | 81 | 107 | 61 | 41 | 252 | 293 | 543 |
| Dec 82 | 83 | 110 | 91 | 36 | 281 | 317 | 602 |
| Jan 83 | 83 | 121 | 82 | 52 | 276 | 328 | 614 |
| Feb 83 | 75 | 104 | 90 | 41 | 244 | 285 | 556 |
| Mar 83 | 83 | 120 | 63 | 47 | 257 | 304 | 571 |
| Apr 83 | 81 | 117 | 51 | 33 | 238 | 271 | 521 |
| May 83 | 83 | 109 | 27 | 43 | 197 | 240 | 460 |
| ANNUAL | 980 | 1302 | 564 | 489 | 2966 | 3455 | 6312 |
| WINTER | 569 | 792 | 475 | 290 | 1786 | 2076 | 3919 |
| SUMMER | 411 | 510 | 89 | 199 | 1180 | 1379 | 2393 |

( winter = oct - apr, summer = may - sep )

Table 11.4c Monthly incidental gains in kWh - House 36

| MONTH | BODY HEAT | HOT WATER | BOILER CASING | GAS COOKER | ELEC. | TOTAL |
|---|---|---|---|---|---|---|
| Jun 82 | 120 | 121 | 26 | 161 | 310 | 738 |
| Jul 82 | 124 | 124 | 26 | 161 | 280 | 715 |
| Aug 82 | 124 | 120 | 21 | 126 | 307 | 698 |
| Sep 82 | 120 | 119 | 27 | 137 | 324 | 728 |
| Oct 82 | 124 | 133 | 63 | 145 | 415 | 880 |
| Nov 82 | 120 | 123 | 84 | 131 | 415 | 873 |
| Dec 82 | 124 | 141 | 124 | 130 | 432 | 951 |
| Jan 83 | 124 | 138 | 110 | 137 | 446 | 955 |
| Feb 83 | 112 | 130 | 133 | 124 | 371 | 870 |
| Mar 83 | 124 | 140 | 89 | 144 | 409 | 906 |
| Apr 83 | 120 | 133 | 75 | 133 | 351 | 812 |
| May 83 | 124 | 135 | 52 | 140 | 382 | 833 |
| ANNUAL | 1460 | 1557 | 830 | 1669 | 4442 | 9959 |
| WINTER | 848 | 938 | 678 | 944 | 2839 | 6247 |
| SUMMER | 612 | 619 | 152 | 725 | 1603 | 3712 |

( winter = oct - apr, summer = may - sep )

Table 11.4d Monthly incidental gains in kWh - House 38

## 11.6 Contribution to heating

Figures quoted in this section are for the total heat inputs from the various sources of internal heat, without any assumptions made about their usefulness in displacing space heating requirement. This has been done because one of the intentions of this field trial was to establish detailed energy balances for individual houses. Other researchers have suggested usefulness factors of 0.7-0.8.

Chapter 12 (Energy balances) deals with detailed breakdowns of energy inputs and outputs. Gross heating requirements are quoted in that section, determined by adding up all the heat inputs from incidental gains, auxiliary space heating and solar gains (with special treatment for end-of-season months, to deal with overheating). The fraction of the gross heat requirement defined in this way, represented by the incidental gains given in this section are:

| | | |
|---|---|---|
| House | 33 | 43% |
| " | 35 | 35% |
| " | 36 | 32% |
| " | 38 | 41% |
| Average | | 38% |

Averaged over the four houses, more than a third of the gross heating requirement is provided by incidental heat gains.

## 11.7 Other estimates of incidental gains

Table 11.5 compares various published estimates for incidental heat gains, including the average of the four Linford houses.

It is not known what assumptions were made about numbers of occupants for the various estimates, except that by Heap, which assumed an average family size of 2.9 persons. This is very close to the average of the Linford houses, and the estimates quoted are similar.

The combined estimates for electricity and cooking heat gains (8.8+2.6 = 11.4 kWh/day) are approximately the same as Wolf and Brundretts (12 kWh/day), but higher than Heap and Siviour/Haslett (8.2 and 9.5 kWh/day), which included a usefulness factor of about 0.7, which has not been applied to the Linford houses.

The estimates for hot water gains at Linford is very similar to those of Heap and Siviour/Haslett, but considerably lower than those of Billington and Brundrett. Estimates will depend heavily on what tank insulation is assumed - the estimate quoted for Linford is a combination of measured data and assumptions made about the amount of heat released to the house from hot water in sinks etc.

The Linford total of 21.7 kWh/day is slightly higher than those of Wolf, Heap, Siviour/Haslett and Leach, but lower than that of Billington and Brundrett. It should be remembered that a usefulness factor has not been applied to Linford, whereas it has for at least Heap and Siviour.

If a usefulness factor of 0.7 were applied, the Linford winter value would be 15.2 kWh/day, which is close to Heap's 15.6 kWh/day (same family size). Similarly, the annual figure would be 14.0 kWh/day, which is close to Leach's 15.2 kWh/day, again with approximately the same family size.

During the design stage, many computer simulations were performed using PASS 1 (Reference 11.5), in order to assess the effects of the insulation and solar measures. Nearly all of this was applied to the Pennylands house design, and conclusions passed on to the Linford design. An hourly profile of incidental gains was assumed in this model, largely based on data from the Electricity Council Research Centre (Reference 11.1). Figure 11.4 shows the original estimate, together with data for house 33. The latter has been scaled down by a usefulness factor of 0.7, as the design estimate was for incidental gains considered directly useful in displacing space heating requirement, and data presented so far in this section is for actual heat inputs from incidental sources, useful or not. The daily totals compare well (16.0 and 16.8 kWh/day), but the differences in the hourly profiles indicate the rather arbitrary process of choosing a suitable profile for design purposes.

Table 11.5 Some published assessments of internal free heat

| Source | In winter (kWh/day) | | | | | | Summer | | Average all year | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Billington (1) | Wolf (2) | Brundrett (3) | Heap (4) | Siviour and Haslett (5) | Linford (6) | Siviour and Haslett (7) | Linford (6) | Leach (8) | Domestic Engineering Services (9) | Linford (6) |
| Occupants (a) | 4.8 | 5.4 | 6 | 4 | 4.7 | 3.7 | 3.5 | 3.7 | - | - | 3.7 |
| Appliance | 9.6 ) | ) 12 ) | ) 12 | 4.8 | 5.4 | 8.8 | 3.5 | 7.2 | 2.3 | 5.9 | 8.2 |
| Cooking | 8.0 ) | ) | | 3.4 | 4.1 | 2.6 | 3.0 | 2.4 | 6.1 | 3.7 | 2.5 |
| Hot water | 15 | - | 11 | 3.4 | 4.3 | 4.1 | 3.0 | 3.6 | 6.8 | 4.8 | 3.9 |
| Boiler casing losses | - | - | - | - | - | 2.5 | - | 0.7 | - | - | 1.7 |
| TOTAL | 37.4 | 17.4 | 29 | 15.6 | 18.5 | 21.7 | 13.0 | 17.6 | 15.2 | 14.4 | 20.0 |

Notes (a) 4 and 8 are for average family size of 2.9 persons.

(1) N.J. Billington. Thermal Insulation and Domestic Fuel Consumption BSE April 1972, p. 23-24.

(2) R. Wolf Chauffage et Conditionnement Electriques des Locaux. (Electric heating and conditioning of dwellings) Eyrolles (Paris) 1974, p. 63.

(3) G.W. Brundrett. Some effects of thermal insulation on design. Applied Energy (1) 1975, p. 7-30.

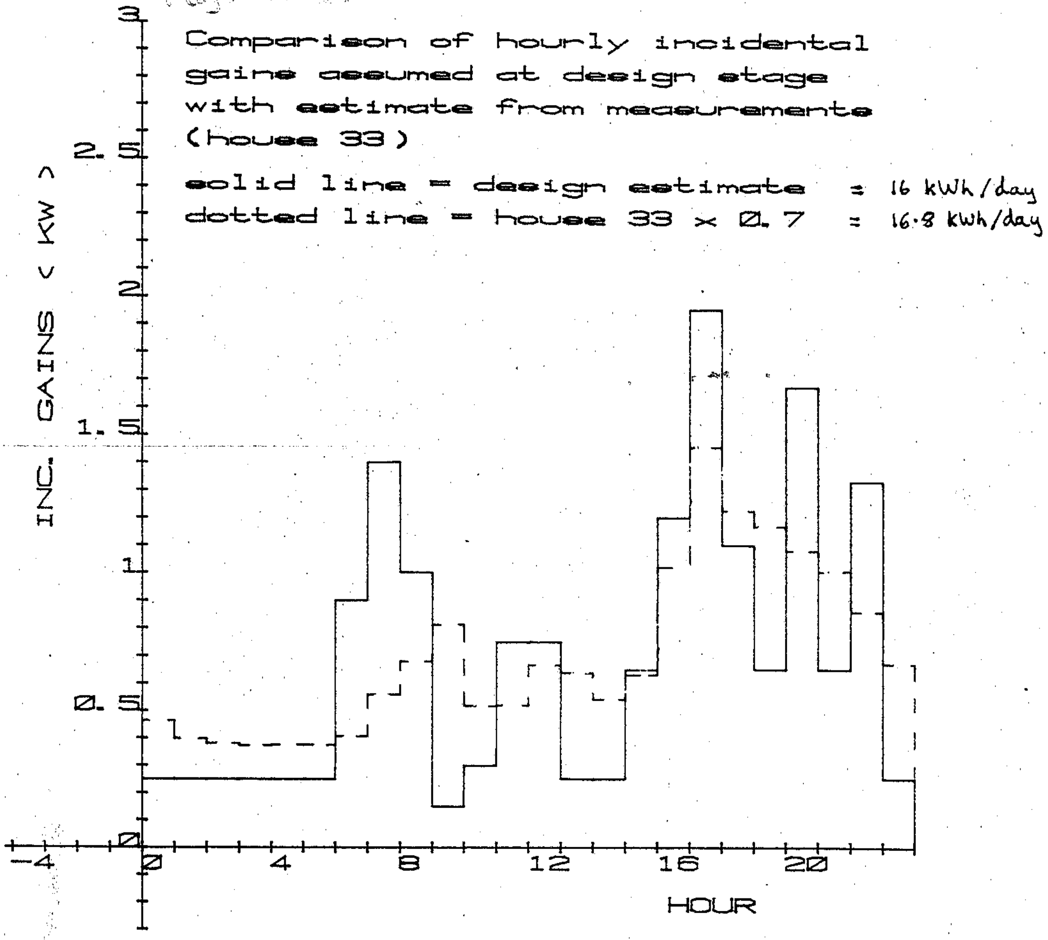
(4) R.D. Heap Assembled at ECRC from Electricity Supply Industry Statistics.

(5) & (7) Compiled by J.B. Siviour and G. Haslett of the Electricity Council for simulated occupancy tests.

(6) Average of four houses shown separately.

(8) S.J. Leach. Energy Consumption in Buildings, Building 23 January, 1976, p. 83-84.

(9) Domestic Engineering Services. IHVE publication 1974, p. 16 (EC data).



Comparison of hourly incidental
gains assumed at design stage
with estimate from measurements
(house 33)
solid line = design estimate = 16 kWh/day
dotted line = house 33 × 0.7 = 16·8 kWh/day
INC. GAINS (KW)
HOUR
0
0.5
1
1.5
2
2.5
3
-4
0
4
8
12
16
20


Figure 11.4

## References


11.1 J.B. Siviour — "Calculating solar heating and free heat and their contribution to space heating in buildings" CIB 517: Meeting at Holzkirken, Munich September 1977

11.2 A. Horton, S. Grove — "Milton Keynes Solar House - performance and cost analysis of solar heating system 1975-1979". Research Report, Built Environment Research Group, Polytechnic of Central London. November 1979.

11.3 S.J. Wozniak — "Solar Heating Systems for the UK: Design, installation and economic aspects". Building Research Establishment Report. Published by HMSO.

11.4 C.E. Uglow — The calculation of energy use in dwellings. Building Services Engineering Research and Technology, Vol. 2 No. 1, 1981.

11.5 R. Everett — Passive Solar in Milton Keynes Open University Energy Research Group Report, ERG 031. July 1980.

# 12. ENERGY BALANCES

CONTENTS



Estimates of fabric and ventilation heat losses and incidental gains have been brought together to formulate monthly energy balances for four occupied houses. The overall picture of the sources and relative magnitudes of the energy inputs and outputs is thus obtained.

## 12. ENERGY BALANCES

This chapter brings together measurements and estimates of various parameters described elsewhere in the report (fabric heat losses, ventilation heat losses, incidental gains etc.), to formulate detailed energy balances for four occupied houses on a monthly basis. This gives an overall picture of the sources and relative magnitudes of the various energy inputs and outputs over the year, and gives estimates of absolute solar gains.

### 12.1 Methodology

The energy balance of a house can be described in simple terms as:

HEAT INPUTS = HEAT OUTPUTS

incidental gains + solar gains + space heating = fabric losses + floor losses + ventilation losses

Floor heat losses have been specified separately to be consistent with the correlation of heating with $\Delta T$ and solar radiation described in Chapter 10, and the analysis of fabric heat losses described in Chapter 8.

The methods of estimating the terms in the energy balance equation are as follows:

(i) Incidental gains.

These have been estimated as:

incidental gains = total electricity (inc. cooking) + boiler casing losses + occupancy gains + hot water gains + gas cooking (if any)

How each of these components were measured or estimated is described in Chapter 11.

(ii) Space heating.

This was measured directly using heat meters.

(iii) Fabric heat losses.

The fabric heat loss coefficients obtained from the correlations of heating with $\Delta T$ and solar radiation described in Chapter 10 were used to calculate fabric heat losses:

$$\text{fabric heat losses} = N \times U_{Fab}\overline{\Delta T} \times \frac{24}{1000} \text{ kWh/month}$$

where $N$ = number of days in month

$U_{Fab}$ = fabric heat loss coefficient in W/deg.C

$\overline{\Delta T}$ = monthly average temperature difference (whole house average - outside).

The heat loss coefficients used were:

| | |
|---|---|
| House 33 | 130 W/deg C |
| House 35 | 129 " |
| House 36 | 139 " |
| House 38 | 165 " |

(iv) Floor losses.

Chapter 8 concludes that the floor heat losses can be estimated on a monthly basis by using a U value of 0.9 W/m² deg C:

$$\text{floor losses} = N \times 0.9 \times \overline{\Delta T} \times \frac{24}{1000} \text{ kWh/month}$$

(v) Ventilation losses.

Ventilation rates were estimated using a prediction formula derived from test house measurements by British Gas, measured leakage characteristics and recordings of window openings, as described in Chapter 9.

$$\text{ventilation losses} = N \times V \times \text{vol} \times 0.338 \times \overline{\Delta T} \times \frac{24}{1000} \text{ kWh/month}$$

where $V$ = average ventilation rate
vol = volume of house = 260 m³.

(vi) Solar gains.

In this case solar gains have been found by difference, to satisfy the energy balance equation:

$$\text{solar gains} = \begin{matrix}\text{fabric}\\\text{losses}\end{matrix} + \begin{matrix}\text{floor}\\\text{losses}\end{matrix} + \begin{matrix}\text{ventilation}\\\text{losses}\end{matrix} - \begin{matrix}\text{space}\\\text{heating}\end{matrix} - \begin{matrix}\text{incidental}\\\text{gains}\end{matrix}$$

The problem with this is that large percentage errors can arise in the estimate of solar gains due to subtracting relatively large quantities from other large quantities, each with their own errors. This is discussed later.

Also, the ends of the heating season are difficult to deal with in deciding how much of the solar gains are useful in displacing space heating, and how much give rise to overheating and/or venting. Estimating the solar gains by difference in this way is not a completely independent method from the correlation analysis in Chapter 10, which produces an average solar aperture. This is because the same assumptions and data are used in each case. For example, the fabric heat loss coefficient obtained from the correlations is used in the energy balance method; assumptions about the floor and ventilation losses and the incidental gains are the same. We could equally approach the problem from the other direction - assume a constant solar aperture of say 10 m² for all months, calculate the absolute solar gains on this basis, and balance up the equation by "losing" the errors in the fabric, ventilation or floor losses. However, this is even worse than the first method in dealing with the ends of the heating season.

In formulating energy balances, it is difficult to decide what is the aim - to derive an energy balance or to calculate the solar gains by difference. It is hoped to satisfy both - if all the various heat inputs can be made to balance the estimated heat losses using assumptions that can be supported by various means, and the individual components take "reasonable" values, again supported by other evidence, we can be fairly confident that we have a self-consistent energy balance that represents our best estimate of the real energy flows, and is somewhere near the truth.

## 12.2 Results

Tables 12.1-12.4 give the complete energy balances for four occupied houses.

| | |
|---|---|
| Columns 1-3 | are measured data for south-facing solar radiation, outside air temperature and whole-house average internal air temperature. |
| Column 4 | is the estimated average ventilation rate calculated by the methods described in Chapter 9. |
| Columns 5-7 | are the estimated fabric, floor and ventilation heat losses calculated by the methods described earlier. The lengthy process of calculating the ventilation rates was not extended over the summer period, and a nominal value of 0.4 ac/h was assumed. |
| Column 8 | is the total heat loss (the sum of columns 5, 6 and 7), i.e. the total amount of heat that flowed out of the house due to the elevation of the internal temperature above outside. |
| Column 9 | is the measured space heating input. |
| Columns 10-13 | are the components of the incidental gains, with the total in Column 14. |
| Column 15 | is the total heat input to the house from internal sources, i.e. the sum of the space heating input and the incidental gains (Column 9 plus Column 14). |
| Column 16 | is the difference between heat losses and internal heat inputs (Column 8-Column 15), and is the estimate of total solar gains into the house, in order to satisfy the heat balance equation. |

During mid-winter months it is assumed that there is no overheating which would "disqualify" some of the solar gains in displacing net space heating. For such months, Column 8 genuinely represents the gross heating requirement. For autumn and spring months, there will be periods when the internal temperature rises above the thermostat setting causing temporary overheating and possible venting by the occupants. As the heat losses in Columns 5-7 are calculated using actual measured internal temperatures,

Table 12.1 Energy balance for house 33, 1982/3

| | | | | | HEAT LOSSES | | | | INTERNAL HEAT INPUTS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Incidental gains | | | | | | | | |
| | sol. rad. (sth) | ext. temp | av. int. temp | av. vent. rate | fab | fl. | ven | TOTAL HEAT LOSS | aux space heat | elec | boil | dhw | occ | tot | TOTAL INT. HEAT INPUT | TOTAL SOLAR INPUT | heat req. for. 19 C | USEFUL SOLAR HEAT |
| | kwh/sqm | C | C | ac/hr | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| jul | 78.3 | 16.9 | 22.6 | 0.40 | 549 | 209 | 147 | 905 | 0 | 232 | 20 | 111 | 155 | 518 | 518 | 387 | 333 | 0 |
| aug | 74.7 | 16.6 | 21.9 | 0.40 | 510 | 195 | 137 | 842 | 0 | 268 | 20 | 111 | 155 | 554 | 554 | 288 | 381 | 0 |
| sep | 80.2 | 14.8 | 21.9 | 0.40 | 662 | 253 | 177 | 1092 | 16 | 291 | 26 | 120 | 150 | 587 | 603 | 489 | 645 | 42 |
| oct | 50.6 | 10.3 | 19.7 | 0.41 | 906 | 346 | 249 | 1501 | 387 | 341 | 53 | 130 | 155 | 679 | 1066 | 435 | 1389 | 323 |
| nov | 41.8 | 7.9 | 19.2 | 0.29 | 1054 | 402 | 205 | 1661 | 685 | 308 | 74 | 129 | 150 | 661 | 1346 | 315 | 1631 | 285 |
| dec | 31.2 | 4.2 | 18.2 | 0.30 | 1349 | 515 | 271 | 2135 | 1110 | 382 | 107 | 147 | 155 | 791 | 1901 | 234 | 2135 | 234 |
| jan | 32.2 | 6.9 | 18.7 | 0.32 | 1137 | 434 | 244 | 1815 | 886 | 382 | 95 | 156 | 155 | 788 | 1674 | 141 | 1815 | 141 |
| feb | 47.8 | 1.6 | 17.8 | 0.35 | 1410 | 538 | 331 | 2279 | 1076 | 350 | 105 | 145 | 140 | 740 | 1816 | 463 | 2279 | 463 |
| mar | 59.1 | 6.4 | 18.9 | 0.26 | 1205 | 460 | 210 | 1875 | 709 | 334 | 88 | 163 | 155 | 740 | 1449 | 426 | 1875 | 426 |
| apr | 75.1 | 7.2 | 19.1 | 0.31 | 1110 | 424 | 231 | 1765 | 520 | 317 | 73 | 161 | 150 | 701 | 1221 | 544 | 1750 | 529 |
| may | 64.9 | 10.5 | 20.0 | 0.22 | 915 | 349 | 135 | 1399 | 206 | 300 | 48 | 151 | 155 | 654 | 860 | 539 | 1251 | 391 |
| jun | 78.0 | 16.1 | 22.4 | 0.40 | 587 | 224 | 157 | 968 | 24 | 206 | 21 | 139 | 150 | 516 | 540 | 428 | 445 | 0 |
| | 709.0 | 10.0 | 20.0 | | 11394 | 4349 | 2494 | 18237 | 5619 | 3711 | 730 | 1663 | 1825 | 7929 | 13548 | 4689 | 15929 | 2834 |

Table 12.2 Energy balance for house 35, 1982/3

| | | | | | HEAT LOSSES | | | | INTERNAL HEAT INPUTS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Incidental gains | | | | | | | | |
| | sol. rad. (sth) | ext. temp | av. int. temp | av. vent. rate | fab | fl. | ven | TOTAL HEAT LOSS | aux space heat | elec | boil | dhw | occ | tot | TOTAL INT. HEAT INPUT | TOTAL SOLAR INPUT | heat req. for. 16.5 C | USEFUL SOLAR HEAT |
| | kwh/sqm | C | C | ac/hr | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| jul | 78.3 | 16.9 | 22.6 | 0.40 | 530 | 203 | 142 | 875 | 0 | 190 | 13 | 99 | 96 | 398 | 398 | 477 | -61 | 0 |
| aug | 74.7 | 16.6 | 21.4 | 0.40 | 461 | 176 | 124 | 761 | 0 | 190 | 13 | 99 | 99 | 401 | 401 | 360 | -15 | 0 |
| sep | 80.2 | 14.8 | 21.3 | 0.40 | 604 | 231 | 162 | 997 | 4 | 196 | 15 | 98 | 96 | 405 | 409 | 588 | 260 | 0 |
| oct | 50.6 | 10.3 | 17.9 | 0.00 | 730 | 279 | 221 | 1230 | 158 | 227 | 27 | 106 | 99 | 459 | 617 | 613 | 1003 | 386 |
| nov | 41.8 | 7.9 | 16.9 | 0.45 | 837 | 320 | 259 | 1416 | 458 | 196 | 47 | 105 | 96 | 444 | 902 | 514 | 1353 | 451 |
| dec | 31.2 | 4.2 | 15.6 | 0.46 | 1095 | 419 | 177 | 1691 | 852 | 229 | 73 | 114 | 99 | 515 | 1367 | 324 | 1691 | 324 |
| jan | 32.2 | 6.9 | 16.1 | 0.24 | 884 | 338 | 184 | 1406 | 681 | 207 | 62 | 110 | 99 | 478 | 1159 | 247 | 1406 | 247 |
| feb | 47.8 | 1.6 | 14.7 | 0.31 | 1137 | 435 | 183 | 1755 | 776 | 190 | 69 | 104 | 89 | 452 | 1228 | 527 | 1755 | 527 |
| mar | 59.4 | 6.4 | 16.2 | 0.24 | 941 | 360 | 120 | 1421 | 458 | 200 | 48 | 112 | 99 | 459 | 917 | 504 | 1421 | 504 |
| apr | 75.1 | 7.2 | 16.6 | 0.67 | 874 | 335 | 394 | 1603 | 307 | 178 | 41 | 116 | 96 | 431 | 738 | 865 | 1603 | 847 |
| may | 64.9 | 10.5 | 16.5 | 0.40 | 576 | 220 | 155 | 951 | 5 | 155 | 16 | 104 | 99 | 374 | 379 | 572 | 951 | 572 |
| jun | 78.0 | 16.1 | 21.7 | 0.40 | 520 | 199 | 140 | 859 | 0 | 156 | 13 | 91 | 96 | 356 | 356 | 503 | 859 | 0 |
| | 709.0 | 10.0 | 18.1 | | 9189 | 3515 | 2261 | 14965 | 3699 | 2314 | 437 | 1258 | 1163 | 5172 | 8871 | 6094 | 12226 | 3858 |

Table 12.3 Energy balance for house 36, 1982/3

| | sol. rad. (sth) | ext. temp | av. int. temp | av. vent. rate | HEAT LOSSES: fab | fl. | ven | TOTAL HEAT LOSS | INTERNAL HEAT INPUTS: aux space heat | Incidental gains: elec | boil | dhw | occ | tot | TOTAL INT. HEAT INPUT | TOTAL SOLAR INPUT | heat req. for. 19 C | USEFUL SOLAR HEAT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | kwh/sqm | C | C | ac/hr | kWh | kWh | kWh | kWh | kWh* | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| jul | 78.3 | 16.9 | 23.7 | 0.40 | 679 | 242 | 170 | 1091 | 0 | 274 | 14 | 101 | 81 | 470 | 470 | 621 | 336 | 0 |
| aug | 74.7 | 16.6 | 22.6 | 0.40 | 619 | 220 | 155 | 994 | 0 | 308 | 18 | 107 | 84 | 517 | 517 | 477 | 397 | 0 |
| sep | 80.2 | 14.8 | 22.4 | 0.40 | 759 | 270 | 190 | 1219 | 0 | 263 | 13 | 95 | 81 | 452 | 452 | 767 | 673 | 221 |
| oct | 50.6 | 10.3 | 19.7 | 0.22 | 970 | 346 | 133 | 1449 | 301 | 278 | 37 | 113 | 84 | 512 | 813 | 636 | 1341 | 528 |
| nov | 41.8 | 7.9 | 19.3 | 0.29 | 1138 | 406 | 207 | 1751 | 669 | 293 | 62 | 108 | 81 | 544 | 1213 | 538 | 1704 | 491 |
| dec | 31.2 | 4.2 | 17.5 | 0.31 | 1372 | 489 | 266 | 2127 | 1205 | 317 | 91 | 110 | 84 | 602 | 1807 | 320 | 2127 | 320 |
| jan | 32.2 | 6.9 | 18.4 | 0.34 | 1187 | 423 | 253 | 1863 | 991 | 328 | 82 | 121 | 84 | 615 | 1606 | 257 | 1863 | 257 |
| feb | 47.8 | 1.6 | 17.2 | 0.37 | 1454 | 518 | 337 | 2309 | 1178 | 285 | 91 | 105 | 76 | 557 | 1735 | 574 | 2309 | 574 |
| mar | 59.4 | 6.4 | 18.5 | 0.25 | 1249 | 445 | 195 | 1889 | 691 | 304 | 64 | 120 | 84 | 572 | 1263 | 626 | 1889 | 626 |
| apr | 75.1 | 7.2 | 19.3 | 0.27 | 1208 | 431 | 204 | 1843 | 476 | 271 | 65 | 118 | 81 | 535 | 1011 | 832 | 1797 | 786 |
| may | 64.9 | 10.5 | 19.5 | 0.21 | 929 | 331 | 122 | 1382 | 143 | 260 | 28 | 109 | 84 | 481 | 624 | 758 | 1305 | 681 |
| jun | 78.0 | 16.1 | 23.1 | 0.40 | 699 | 249 | 175 | 1123 | 0 | 294 | 18 | 102 | 81 | 495 | 495 | 628 | 465 | 0 |
| | 709.0 | 10.0 | 20.1 | | 12263 | 4370 | 2407 | 19040 | 5654 | 3475 | 583 | 1309 | 985 | 6352 | 12006 | 7034 | 15134 | 4484 |

Table 12.4 Energy balance for house 38, 1982/3

| | sol. rad. (sth) | ext. temp | av. int. temp | av. vent. rate | HEAT LOSSES: fab | fl. | ven | TOTAL HEAT LOSS | INTERNAL HEAT INPUTS: aux space heat | Incidental gains: elec | boil | dhw | occ | cook | tot | TOTAL INT. HEAT INPUT | TOTAL SOLAR INPUT | heat req. for. 20 C | USEFUL SOLAR HEAT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | kwh/sqm | C | C | ac/hr | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh | kWh |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 13a | 14 | 15 | 16 | 17 | 18 |
| jul | 78.3 | 16.9 | 23.6 | 0.40 | 822 | 246 | 173 | 1241 | 0 | 280 | 26 | 124 | 124 | 161 | 715 | 715 | 526 | 574 | 0 |
| aug | 74.7 | 16.6 | 24.1 | 0.40 | 920 | 276 | 194 | 1390 | 0 | 307 | 21 | 120 | 124 | 126 | 698 | 698 | 692 | 630 | 0 |
| sep | 80.2 | 14.8 | 22.8 | 0.40 | 950 | 285 | 200 | 1435 | 20 | 324 | 28 | 120 | 120 | 137 | 729 | 749 | 686 | 932 | 183 |
| oct | 50.6 | 10.3 | 21.1 | 0.25 | 1325 | 397 | 174 | 1896 | 564 | 415 | 63 | 133 | 124 | 145 | 880 | 1444 | 452 | 1702 | 258 |
| nov | 41.8 | 7.9 | 20.6 | 0.29 | 1508 | 452 | 230 | 2190 | 891 | 423 | 84 | 123 | 120 | 131 | 881 | 1772 | 418 | 2086 | 314 |
| dec | 31.2 | 4.2 | 19.9 | 0.32 | 1927 | 578 | 325 | 2830 | 1481 | 444 | 124 | 142 | 124 | 130 | 964 | 2445 | 385 | 2830 | 385 |
| jan | 32.2 | 6.9 | 20.1 | 0.35 | 1620 | 486 | 299 | 2405 | 1357 | 458 | 110 | 138 | 124 | 137 | 967 | 2324 | 81 | 2386 | 62 |
| feb | 47.8 | 1.6 | 19.9 | 0.39 | 2029 | 608 | 417 | 3054 | 1842 | 383 | 134 | 130 | 112 | 124 | 883 | 2725 | 329 | 3054 | 329 |
| mar | 59.1 | 6.4 | 19.4 | 0.27 | 1595 | 478 | 227 | 2300 | 885 | 409 | 89 | 140 | 124 | 144 | 906 | 1791 | 509 | 2300 | 509 |
| apr | 75.1 | 7.2 | 19.4 | 0.28 | 1449 | 434 | 213 | 2096 | 671 | 351 | 75 | 133 | 120 | 133 | 812 | 1483 | 613 | 2096 | 613 |
| may | 64.9 | 10.5 | 20.2 | 0.22 | 1190 | 357 | 138 | 1685 | 332 | 382 | 53 | 135 | 124 | 140 | 834 | 1166 | 519 | 1650 | 484 |
| jun | 78.0 | 16.1 | 23.4 | 0.40 | 867 | 260 | 182 | 1309 | 0 | 310 | 34 | 122 | 120 | 156 | 742 | 742 | 567 | 699 | 0 |
| | 709.0 | 10.0 | 21.2 | | 16202 | 4857 | 2772 | 23831 | 8043 | 4486 | 841 | 1560 | 1460 | 1664 | 10011 | 18054 | 5777 | 20939 | 3137 |

the total heat loss in Column 8 does not represent the true gross heating requirement - part of it must be discounted on the grounds that the house would have been heated to a lower temperature had there been no solar gains.

In order to account for this, it has been assumed that the average whole-house temperature would have been somewhat lower. For house 36, for example, it has been assumed that the occupants would have chosen to heat the house to an average of 19°C during months outside the mid-winter period. Thus Column 17 is the estimated gross heating requirement had there been no solar gains to raise temperatures above the set point. It is actually calculated by scaling down Column 8 by a factor $\frac{19 - T_o}{T_n - T_o}$ where $T_o$ is the outside temperature (Column 2) and $T_n$ is the internal temperature (Column 3), for months when the internal temperature rose above 19°C. For the mid-winter months, the figures in Column 8 are left unchanged, even though measured temperatures fall below 19°C - this is due to more rapid overnight cooling during colder weather depressing the average temperature below the thermostat setting (about 19°C from hourly data). For the other houses, these "cut-off" temperatures were taken as:

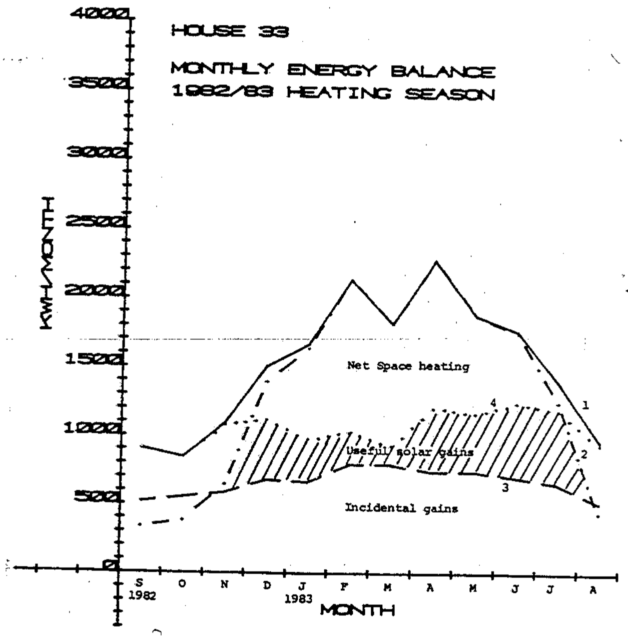
| | |
|---|---|
| House 33 | 19°C |
| House 35 | 16.5°C |
| House 38 | 20°C |

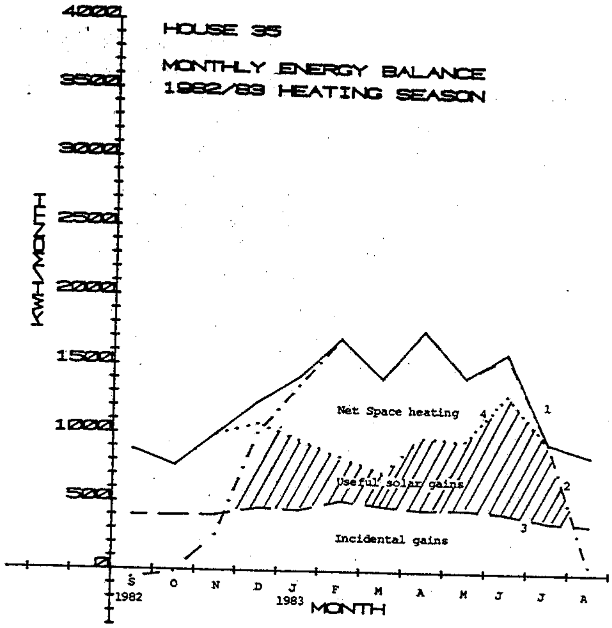
Finally, Column 18 is the estimated useful solar gains, obtained by deducting the internal heat inputs (Column 16) from the new gross heating requirement (Column 17).

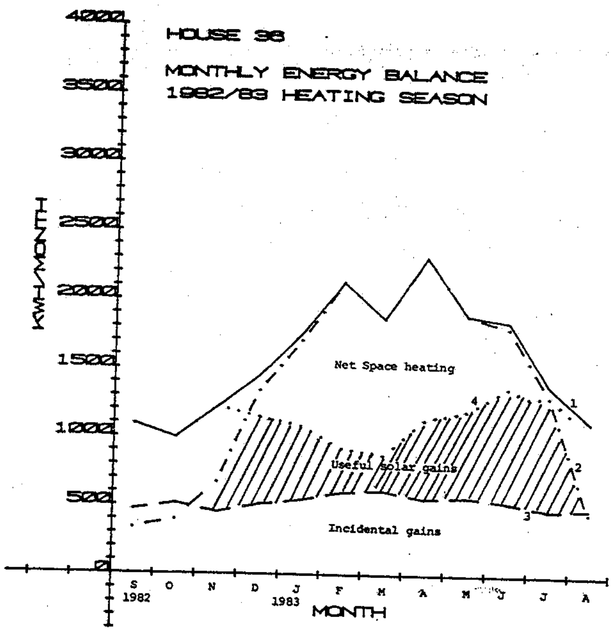
The choice of the cut-off temperatures is slightly arbitrary, as there is no real way of knowing what the average temperature would have been without the overheating by solar gains. Furthermore, should overheating simply be regarded as overheating - the effects are certainly not severe, and the temperature elevations due to excess solar gains at the ends of the heating season are almost certainly enjoyed by the occupants. If the cut-off temperature was increased in each case to 21°C, the useful solar gains would increase by between 800 kWh and 1700 kWh. This is very much oversimplified, however, and a much more detailed discussion can be found in Chapter 10.

Figure 12.1 illustrates the data in the tables. Curve 1 is the gross heating requirement defined by Column 8 in the tables (i.e. the total heat losses). Curve 2 is the re-defined gross heating requirement (Column 17). Curve 3 is the sum of the incidental gains. Curve 4 is the result of deducting the net space heating from Curve 1. Thus the area bounded by Curves 2, 3 and 4 is equal to the useful solar gains (Column 18).

For the period September-May, the breakdown of energy input that contributed to the heating of the houses is given in Figure 12.2.



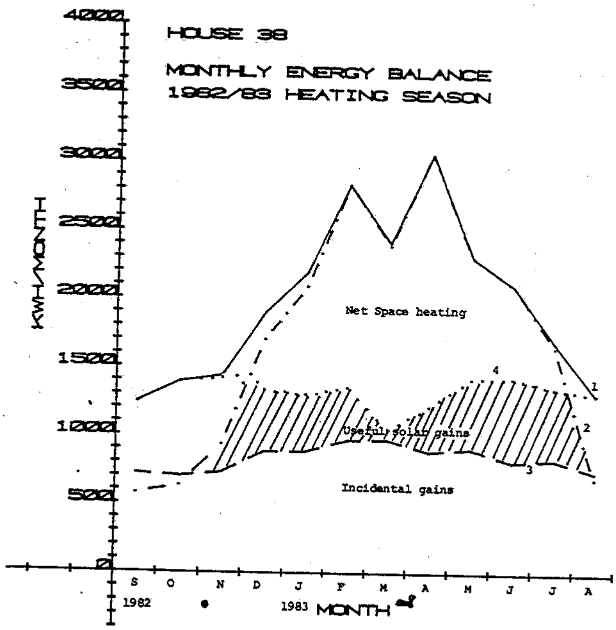
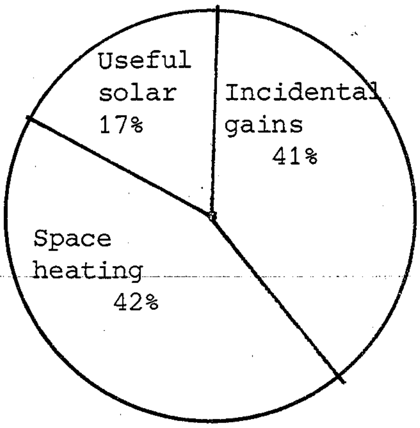




Figure 12.1 Monthly energy balances

Figure 12.2 Components of useful energy input to heated space, September-May.



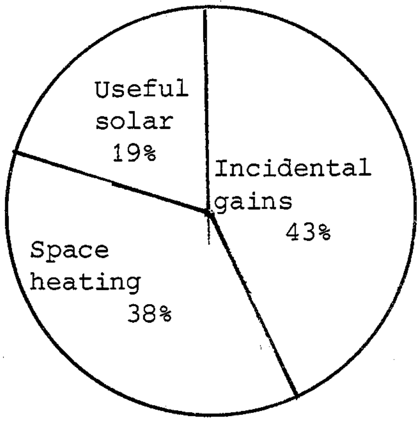

House 38

incidental gains = 7856 kWh

space heating = 8043 kWh

useful solar gains = 3137 kWh

Total = 19036 kWh.



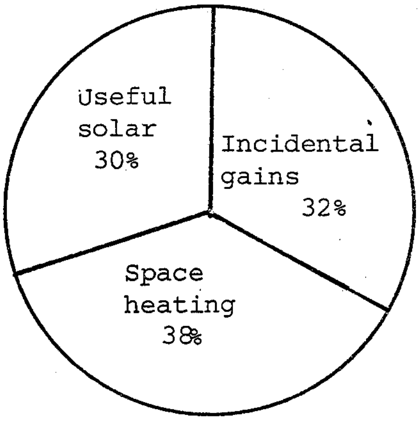

House 33

incidental gains = 6341 kWh

space heating = 5595 kWh

useful solar gains = 2834 kWh

Total = 14770 kWh



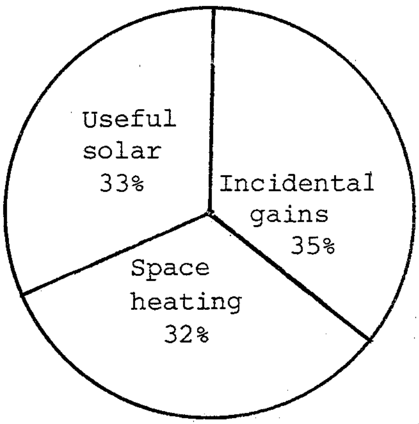

House 36

incidental gains = 4870 kWh

space heating = 5654 kWh

useful solar gains = 4484 kWh

Total = 15008 kWh



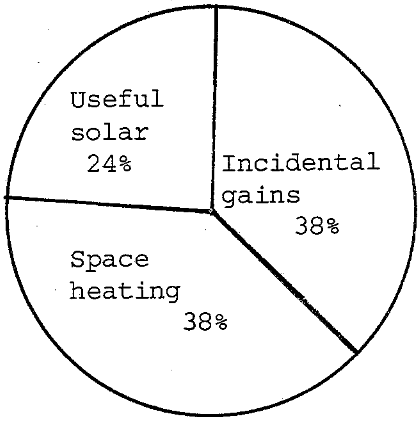

House 35

incidental gains = 4017 kWh

space heating = 3699 kWh

useful solar gains = 3858 kWh

Total = 11574 kWh




Average of all four

incidental gains = 5771 kWh

space heating = 5748 kWh

useful solar gains = 3573 kWh

Total = 15092 kWh

N.B. The data used for these balances is over a slightly different period to the data presented in Chapter 5, hence the discrepancies.

Sankey diagrams for each of the four houses are shown in Figure 12.3.

## 12.3 Check against solar apertures

Table 12.5 shows monthly average solar apertures obtained by dividing the useful solar gains from the energy balance tables by the incident south-facing solar radiation intensities. They should be compared with the solar apertures obtained from correlations in Chapter 10:

| | |
|---|---|
| House 33 | 6.8 ± 0.6 $m^2$ |
| House 35 | 9.4 ± 0.8 $m^2$ |
| House 36 | 10.7 ± 1.0 $m^2$ |
| House 38 | 7.9 ± 0.8 $m^2$ |

| | House | | | |
|---|---|---|---|---|
| Month | 33 | 35 | 36 | 38 |
| October | 6.4 | 7.6 | 10.4 | 5.1 |
| November | 6.8 | 10.7 | 11.7 | 7.5 |
| December | 7.5 | 10.4 | 10.2 | 12.3 |
| January | 4.4 | 7.7 | 8.0 | 1.9 |
| February | 9.7 | 11.0 | 12.0 | 6.9 |
| March | 7.2 | 8.5 | 10.5 | 8.6 |
| April | 7.0 | 11.3 | 10.5 | 8.2 |
| Average | 7.1 | 9.7 | 10.6 | 7.3 |

Table 12.5: Retrospective solar apertures, calculated from useful solar gains obtained from energy balances.

Because the energy balances are calculated using the same assumptions as for the correlations in Chapter 10 from which solar apertures are obtained, the average solar apertures in Table 12.5 should be very close to those obtained from the correlations in the first place, and indeed this is so. There can be considerable deviations from the average on a monthly basis, however, due to the compounding of errors of estimation in the various terms in the energy balance equation. These errors appear in the estimate of useful solar gains. For example, in January an error of only ± 30 kWh in the fabric heat loss alone (about 1000 kWh) will cause an error of ± 1 $m^2$ in the solar aperture.

Estimating absolute solar gains from energy balances is therefore equivalent to assuming a constant solar aperture over the biggest part of the heating season (October-April in this case), plus

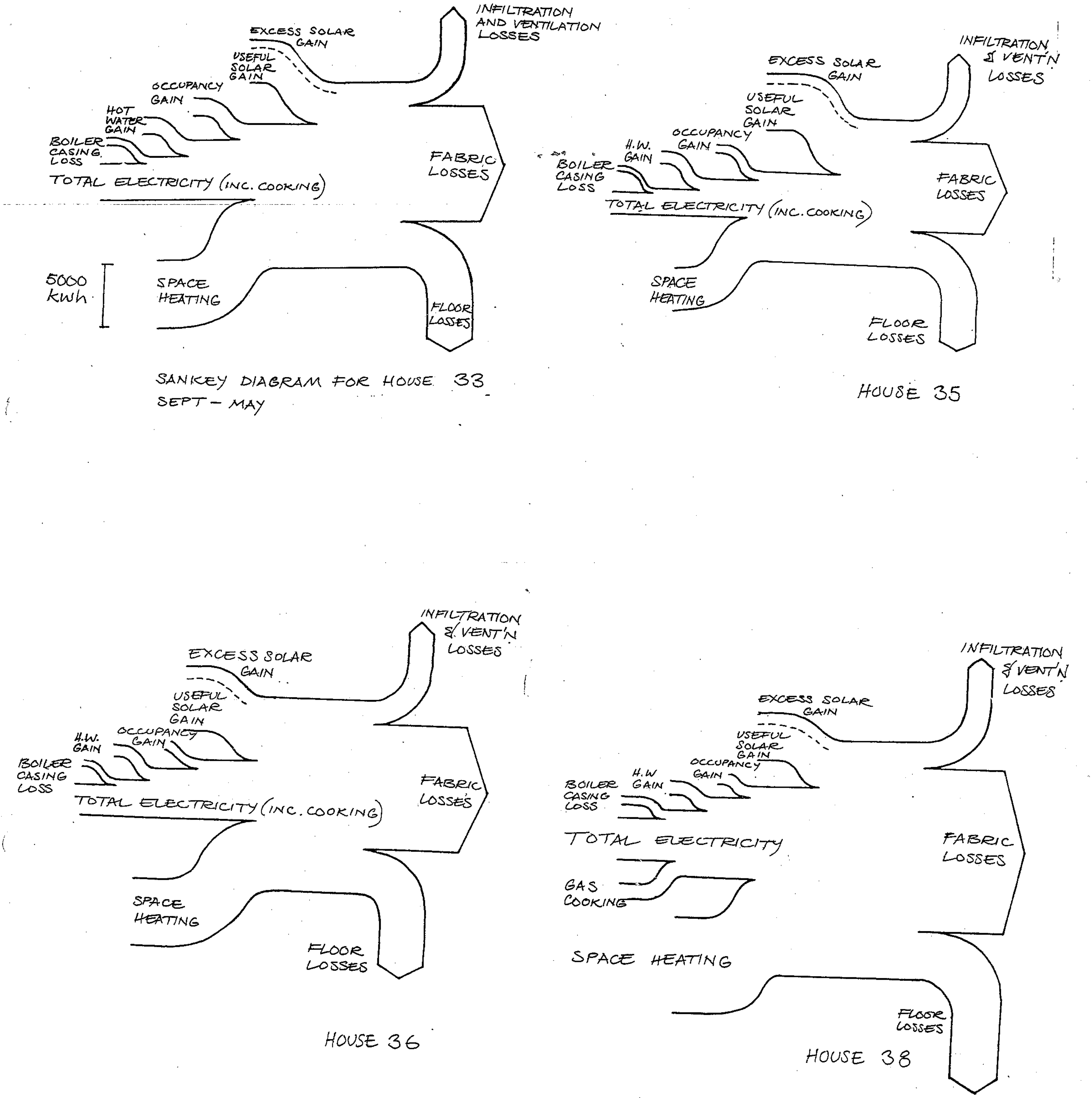



Figure 12.3   Sankey diagrams for four houses (September-May).

making further estimates for September and May using average internal temperature as a scaling factor to distinguish between useful and excess solar gains.

Absolute solar gains are, in isolation, fairly useless in assessing the benefits of passive solar design. Of much more interest is the "marginal" passive solar energy savings i.e. the difference in energy consumption between "normal", randomly oriented, overshaded houses and houses incorporating deliverate passive solar design. This is analysed in Chapter 10.

# 13. COMFORT CONDITIONS

CONTENTS



Measurement of air temperatures in the occupied houses formed a large part of the monitoring. This chapter gives a detailed analysis of those temperatures, showing for example, differences in seasonal averages, short-term temperature profiles, the stabilising effect of the thermal mass, and summer comfort conditions.

# 13. INTERNAL TEMPERATURES AND COMFORT CONDITIONS

## 13.1 Introduction

For a given house design, the space heating requirement is largely dependent on long term averages of internal and external temperatures. The occupants' perception of comfort however, not only depends on their choice of temperature, as set by the heating system thermostats, but is strongly influenced by short term changes in internal temperature, caused by cooling overnight and between heating periods, or by overheating during periods of excessive solar gain. Both of these are strongly affected by thermal mass.

This chapter therefore presents an analysis of the internal air temperatures in the occupied houses, which shows:

(i) long term average temperatures in various rooms of each house, and differences between houses.

(ii) short term temperature profiles during various winter conditions, including a period of extremely cold weather.

(iii) the effect of the thermal mass in stabilising internal temperatures.

(iv) conditions during hot summer weather.

As appendix 13.1 shows that estimated mean radiant temperatures are very close to air temperatures, the latter is used throughout, as a representative measure of comfort.

## 13.2 Monthly and Seasonal Averages

The full list of monthly average temperatues for six rooms, in six houses over the period November 1981 to June 1983 is shown in table 13.1; the data are plotted in figure 13.1. Included in table 13.1 are average whole-house temperatures. These were calculated by simplified volume-weighting as follows:

$$T_H = \frac{2T_1 + T_2 + T_3 + 2T_4 + T_5 + T_6}{8}$$

where $T_H$ = whole-house average

$T_1$ = living/dining room

$T_2$ = kitchen

Table 13.1 Monthly Average Room Temperatures

| HOUSE 33 | DOWNSTAIRS LIV | DOWNSTAIRS KIT | DOWNSTAIRS HALL | UPSTAIRS (BEDROOMS) STH | UPSTAIRS (BEDROOMS) STH | UPSTAIRS (BEDROOMS) NTH | WHOLE HOUSE AV. |
|---|---|---|---|---|---|---|---|
| 1981 Nov | 21.3 | 21.8 | 20.7 | 18.9 | 19.7 | 20.1 | 20.3 |
| Dec | 20.7 | 21.1 | 19.9 | 18.6 | 19.1 | 19.5 | 19.8 |
| 1982 Jan | 20.7 | 21.3 | 19.7 | 18.2 | 18.8 | 19.1 | 19.6 |
| Feb | 20.2 | 21.2 | 19.6 | 18.1 | 18.6 | 19.2 | 19.4 |
| Mar | 20.3 | 20.6 | 19.1 | 18.3 | 19.0 | 19.0 | 19.4 |
| Apr | 20.3 | 20.7 | 19.6 | 19.2 | 19.7 | 19.7 | 19.8 |
| May | 21.2 | 21.6 | 20.8 | 21.3 | 21.8 | 21.7 | 21.3 |
| Jun | 22.0 | 22.5 | 21.8 | 22.5 | 22.9 | 22.9 | 22.4 |
| Jul | 22.2 | 22.7 | 22.0 | 22.7 | 23.0 | 22.9 | 22.6 |
| Aug | 22.0 | 22.2 | 21.3 | 21.6 | 22.2 | 22.0 | 21.9 |
| Sep | 21.8 | 22.3 | 21.4 | 21.9 | 22.2 | 22.1 | 21.9 |
| Oct | 20.0 | 20.7 | 19.7 | 19.1 | 19.3 | 19.4 | 19.7 |
| Nov | 20.0 | 20.8 | 19.3 | 18.4 | 17.7 | 18.9 | 19.2 |
| Dec | 19.3 | 20.1 | 18.4 | 17.1 | 16.3 | 17.7 | 18.2 |
| 1983 Jan | 19.7 | 20.5 | 18.8 | 17.6 | 17.2 | 18.4 | 18.7 |
| Feb | 19.0 | 19.6 | 18.0 | 16.6 | 16.2 | 17.3 | 17.8 |
| Mar | 19.6 | 20.1 | 18.8 | 18.0 | 18.0 | 18.8 | 18.9 |
| Apr | 19.8 | 20.5 | 19.0 | 18.3 | 18.4 | 19.1 | 19.1 |
| May | 20.0 | 20.9 | 19.7 | 19.5 | 19.7 | 20.3 | 20.0 |

| HOUSE 35 | DOWNSTAIRS LIV | DOWNSTAIRS KIT | DOWNSTAIRS HALL | UPSTAIRS (BEDROOMS) STH | UPSTAIRS (BEDROOMS) STH | UPSTAIRS (BEDROOMS) NTH | WHOLE HOUSE AV. |
|---|---|---|---|---|---|---|---|
| 1981 Nov | 17.7 | 14.6 | 16.3 | 15.6 | 14.6 | 14.1 | 15.8 |
| Dec | 17.0 | 14.6 | 14.5 | 13.1 | 11.4 | 10.9 | 14.9 |
| 1982 Jan | 17.2 | 16.8 | 14.9 | 14.0 | 12.7 | 11.8 | 14.8 |
| Feb | 17.4 | 17.2 | 15.6 | 14.6 | 13.7 | 12.7 | 15.4 |
| Mar | 18.2 | 17.6 | 16.4 | 16.2 | 15.3 | 14.2 | 16.8 |
| Apr | 17.0 | 16.2 | 15.7 | 16.6 | 16.3 | 15.0 | 16.3 |
| May | 20.5 | 20.6 | 19.5 | 20.6 | 20.3 | 19.4 | 20.3 |
| Jun | 21.7 | 22.0 | 21.2 | 22.1 | 21.4 | 21.2 | 21.7 |
| Jul | 22.6 | 22.9 | 22.1 | 23.0 | 22.1 | 22.3 | 22.6 |
| Aug | 22.0 | 22.0 | 21.2 | 21.3 | 21.1 | 20.6 | 21.4 |
| Sep | 21.9 | 21.9 | 20.9 | 21.3 | 20.9 | 20.6 | 21.3 |
| Oct | 18.8 | 19.3 | 17.8 | 17.4 | 17.0 | 16.9 | 17.9 |
| Nov | 18.1 | 18.5 | 16.9 | 16.0 | 15.8 | 15.7 | 16.9 |
| Dec | 17.5 | 17.8 | 15.8 | 14.2 | 14.2 | 14.1 | 15.6 |
| 1983 Jan | 17.5 | 17.5 | 16.2 | 15.1 | 14.6 | 15.0 | 16.1 |
| Feb | 16.8 | 15.8 | 14.7 | 13.3 | 13.4 | 13.1 | 14.7 |
| Mar | 17.4 | 17.2 | 16.1 | 15.7 | 15.2 | 15.1 | 16.2 |
| Apr | 18.0 | 17.7 | 16.4 | 15.9 | 15.2 | 15.5 | 16.6 |
| May | 16.8 | 17.2 | 16.2 | 16.6 | 15.7 | 16.2 | 16.5 |

| HOUSE 36 | DOWNSTAIRS LIV | DOWNSTAIRS KIT | DOWNSTAIRS HALL | UPSTAIRS (BEDROOMS) STH | UPSTAIRS (BEDROOMS) STH | UPSTAIRS (BEDROOMS) NTH | WHOLE HOUSE AV. |
|---|---|---|---|---|---|---|---|
| 1982 Nov | 19.4 | 18.0 | 17.8 | 17.6 | 17.7 | 18.3 | 18.2 |
| Dec | 18.4 | 17.2 | 17.5 | 16.8 | 17.2 | 17.4 | 17.5 |
| 1982 Jan | 19.6 | 18.3 | 19.2 | 18.0 | 18.2 | 18.4 | 18.7 |
| Feb | 19.8 | 18.6 | 18.4 | 18.3 | 18.3 | 18.9 | 18.8 |
| Mar | 20.1 | 18.3 | 18.2 | 18.9 | 19.1 | 19.2 | 19.1 |
| Apr | 20.7 | 18.7 | 18.7 | 19.1 | 19.4 | 19.7 | 19.5 |
| May | 22.4 | 20.3 | 20.4 | 21.2 | 21.7 | 21.6 | 21.4 |
| Jun | 23.8 | 22.1 | 22.0 | 23.0 | 23.3 | 23.5 | 23.1 |
| Jul | 24.4 | 22.6 | 22.5 | 23.8 | 24.1 | 24.2 | 23.7 |
| Aug | 23.7 | 21.8 | 21.9 | 22.3 | 22.4 | 22.6 | 22.6 |
| Sep | 23.6 | 21.6 | 21.7 | 22.0 | 22.3 | 22.4 | 22.4 |
| Oct | 21.0 | 19.3 | 19.4 | 19.0 | 19.0 | 19.6 | 19.7 |
| Nov | 20.6 | 19.1 | 19.3 | 18.7 | 18.5 | 19.2 | 19.3 |
| Dec | 18.8 | 17.4 | 17.6 | 17.0 | 16.1 | 17.4 | 17.5 |
| 1983 Jan | 19.8 | 18.3 | 18.3 | 17.8 | 17.3 | 18.1 | 18.4 |
| Feb | 18.7 | 16.9 | 17.3 | 16.5 | 16.6 | 16.6 | 17.2 |
| Mar | 19.9 | 18.0 | 18.5 | 17.7 | 18.1 | 18.3 | 18.5 |
| Apr | 20.6 | 18.5 | 19.0 | 18.7 | 19.1 | 19.1 | 19.3 |
| May | 20.7 | 18.7 | 19.1 | 18.8 | 19.4 | 19.7 | 19.5 |

| HOUSE 38 | LIV | KIT | HALL | STH | STH | NTH | WHOLE HOUSE AV. |
|---|---|---|---|---|---|---|---|
| 1981 Nov | 20.6 | 20.9 | 20.6 | 20.0 | 19.9 | 18.7 | 20.2 |
| Dec | 20.4 | 20.7 | 20.3 | 18.7 | 18.9 | 18.1 | 19.5 |
| 1982 Jan | 20.4 | 21.0 | 20.5 | 19.7 | 19.4 | 18.1 | 19.9 |
| Feb | 20.4 | 21.1 | 20.3 | 20.3 | 19.1 | 18.4 | 20.0 |
| Mar | 20.5 | 20.5 | 20.3 | 19.4 | 19.6 | 18.1 | 20.0 |
| Apr | 21.4 | 21.5 | 20.4 | 21.3 | 21.3 | 19.9 | 21.2 |
| May | 21.7 | 21.6 | 21.7 | 22.4 | 22.5 | 21.2 | 21.9 |
| Jun | 22.9 | 23.4 | 23.2 | 23.7 | 23.9 | 22.9 | 23.4 |
| Jul | 23.2 | 24.0 | 23.5 | 24.0 | 24.2 | 23.1 | 23.6 |
| Aug | 24.0 | 24.3 | 24.1 | 24.3 | 24.7 | 23.4 | 24.1 |
| Sep | 22.7 | 23.0 | 22.9 | 22.9 | 23.2 | 21.9 | 22.8 |
| Oct | 21.4 | 21.5 | 21.5 | 20.7 | 21.1 | 20.0 | 21.1 |
| Nov | 20.9 | 20.9 | 21.0 | 20.3 | 20.8 | 19.6 | 20.6 |
| Dec | 20.7 | 20.3 | 20.5 | 19.5 | 19.9 | 18.7 | 19.9 |
| 1983 Jan | 20.6 | 20.2 | 20.5 | 19.8 | 20.3 | 19.1 | 20.1 |
| Feb | 20.8 | 20.2 | 20.5 | 19.3 | 19.8 | 18.6 | 19.9 |
| Mar | 20.4 | 20.3 | 20.4 | 19.5 | 20.0 | 18.8 | 19.9 |
| Apr | 19.8 | 20.0 | 19.8 | 19.0 | 19.5 | 18.4 | 19.4 |
| May | 20.3 | 20.7 | 20.6 | 19.9 | 20.4 | 19.3 | 20.2 |

| HOUSE 39 | LIV | KIT | HALL | STH | STH | NTH | WHOLE HOUSE AV. |
|---|---|---|---|---|---|---|---|
| 1981 Nov* | 12.1 | 11.6 | 11.6 | 12.1 | 12.3 | 11.7 | 12.0 |
| Dec** | 15.9 | 15.0 | 14.5 | 15.0 | 15.1 | 14.5 | 15.1 |
| 1982 Jan | 18.8 | 17.7 | 17.3 | 18.0 | 18.1 | 17.2 | 18.0 |
| Feb | 19.2 | 19.5 | 18.2 | 18.5 | 18.5 | 17.7 | 18.7 |
| Mar | 19.9 | 19.7 | 18.5 | 19.3 | 19.3 | 17.8 | 19.2 |
| Apr | 20.5 | 21.0 | 18.9 | 20.1 | 20.0 | 18.6 | 20.0 |
| May | 19.3 | 18.6 | 17.7 | 20.2 | 20.4 | 19.5 | 19.4 |
| Jun | 22.1 | 22.3 | 21.2 | 22.8 | 23.1 | 23.4 | 22.5 |
| Jul | 22.9 | 22.9 | 21.9 | 23.5 | 23.7 | 23.8 | 23.2 |
| Aug | 23.3 | 23.4 | 22.3 | 23.7 | 24.0 | 23.9 | 23.4 |
| Sep | 21.7 | 21.6 | 20.6 | 22.0 | 22.2 | 22.0 | 21.7 |
| Oct | 20.0 | 20.1 | 18.9 | 19.3 | 19.2 | 19.4 | 19.5 |
| Nov | 20.2 | 20.4 | 19.1 | 19.7 | 19.7 | 19.8 | 19.9 |
| Dec | 19.9 | 19.7 | 18.5 | 18.5 | 18.8 | 18.7 | 19.1 |
| 1983 Jan | 20.0 | 19.9 | 18.8 | 19.0 | 19.4 | 19.3 | 19.4 |
| Feb | 19.5 | 18.7 | 17.9 | 18.0 | 18.4 | 18.0 | 18.5 |
| Mar | 20.0 | 19.7 | 18.7 | 18.7 | 18.9 | 18.9 | 19.2 |
| Apr | 20.5 | 20.2 | 19.2 | 19.9 | 19.7 | 19.8 | 20.0 |
| May | 20.5 | 20.4 | 19.4 | 20.0 | 19.9 | 20.2 | 20.1 |

| HOUSE 40 | LIV | KIT | HALL | STH | STH | NTH | WHOLE HOUSE AV. |
|---|---|---|---|---|---|---|---|
| 1981 Nov | 19.5 | 19.0 | 18.0 | 19.0 | 19.0 | 18.2 | 18.9 |
| Dec | 18.5 | 18.2 | 17.5 | 16.9 | 17.4 | 16.4 | 17.5 |
| 1982 Jan | 19.3 | 18.6 | 18.2 | 17.2 | 18.2 | 17.5 | 18.2 |
| Feb | 20.2 | 19.2 | 18.6 | 18.2 | 18.4 | 18.2 | 18.9 |
| Mar | 21.2 | 19.5 | 19.8 | 20.2 | 20.6 | 19.2 | 20.2 |
| Apr | 19.8 | 18.7 | 18.0 | 19.7 | 20.2 | 18.5 | 19.3 |
| May | 20.3 | 19.5 | 18.7 | 21.2 | 20.3 | 20.2 | 20.1 |
| Jun | 21.7 | 21.6 | 20.6 | 23.2 | 22.0 | 22.2 | 21.9 |
| Jul | 22.2 | 22.0 | 21.0 | 23.8 | 22.2 | 22.5 | 22.3 |
| Aug | 22.1 | 21.5 | 20.7 | 23.2 | 21.6 | 22.3 | 21.9 |
| Sep | 21.5 | 21.1 | 20.2 | 22.6 | 21.1 | 21.6 | 21.4 |
| Oct | 20.2 | 19.9 | 19.1 | 20.5 | 19.5 | 19.9 | 19.9 |
| Nov | 20.1 | 19.7 | 19.3 | 20.3 | 19.7 | 19.6 | 19.8 |
| Dec | 19.5 | 19.0 | 18.9 | 19.6 | 19.3 | 18.9 | 19.2 |
| 1983 Jan | 19.7 | 19.0 | 18.9 | 19.2 | 18.9 | 18.6 | 19.1 |
| Feb | 19.4 | 18.2 | 17.8 | 18.8 | 18.0 | 18.2 | 18.5 |
| Mar | 20.3 | 19.3 | 18.9 | 20.3 | 19.2 | 19.1 | 19.6 |
| Apr | 20.6 | 19.6 | 18.9 | 20.3 | 18.7 | 18.1 | 19.5 |
| May | 19.9 | 19.6 | 18.7 | 20.3 | 19.1 | 18.5 | 19.4 |

*UNOCCUPIED **PARTIALLY OCCUPIED

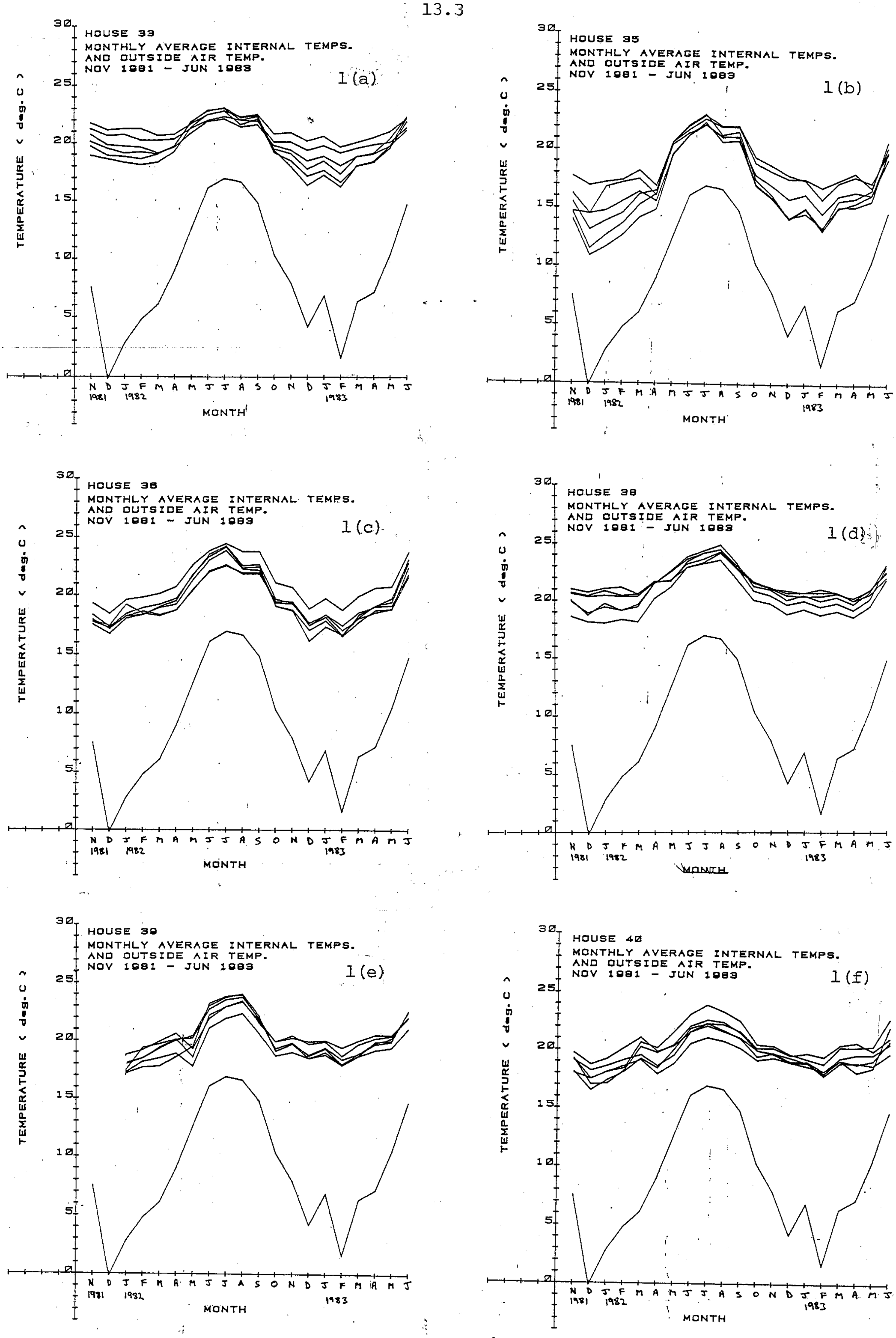



Figure 13.1 Monthly average internal room temperatures

$T_3$ = hall

$T_4$ = bedroom 1 (main, south)

$T_5$ = bedroom 2 (south)

$T_6$ = bedroom 3 (north).

The units are °C.

To make comparison easier, the whole-house average temperatures are reproduced on their own in table 13.2, together with the average outside air temperature.

Table 13.3 gives seasonal values for single-room and whole-house average temperatures.

### 13.2.1 Discussion

Some variations can be seen between houses (referring to Figure 13.1).

Numbers 38, 39 and 40 are heated to very high levels of comfort, with very uniform temperatures around the house. House 38 has the highest whole-house average temperature of 20.1°C for the winter period October 1982-April 1983, with houses 39 and 40 each having values of 19.4°C. Individual room temperatures fall within narrow bands of between 2°C and 3°C. Temperatures in these three houses are also very constant throughout this winter period, varying hardly at all with outside temperature. Some dependence on outside temperatures can be seen, however, for the colder winter of 1981/82.

Average temperatures in house 36 also lie within a narrow band of 2-3°C at any given time, but are slightly lower than 38, 39 and 40 and show more variation with outside air temperature. The seasonal whole house average (October 1982-April 1983) is 18.6°C. Downstairs rooms varied between 17°C and 21°C, and upstairs rooms between 16°C and 19°C.

House 33 has a similar whole-house average temperature to house 36 for the same period (18.8°C), but temperatures varied more widely around the house - within a range of about 4°C at any given time. Downstairs rooms were between 18°C and 21°C, and upstairs between 16°C and 19°C. It is notable that the whole-house average temperature for the 1982/83 heating season was almost 1°C lower than that for 1981/82, probably due to a lowering of thermostat settings.

Clearly, all rooms are heated, to varying degrees in houses 33, 36, 38, 39 and 40. In three of the houses, bedrooms are heated to similar temperatures to living rooms, while the difference is greater for the other two.

Table 13.2 Monthly whole-house average temperatures

| MONTH | | HOUSE 33 | 35 | 36 | 38 | 39 | 40 | AMBIENT TEMP. |
|---|---|---|---|---|---|---|---|---|
| 1981 | Nov | 20.3 | 15.8 | 18.2 | 20.2 | 12.0 | 18.9 | 7.5 |
| | Dec | 19.8 | 14.9 | 17.5 | 19.5 | 15.1 | 17.5 | -0.2 |
| 1982 | Jan | 19.6 | 14.8 | 18.7 | 19.9 | 18.0 | 18.2 | 2.8 |
| | Feb | 19.4 | 15.4 | 18.8 | 20.0 | 18.7 | 18.9 | 4.8 |
| | Mar | 19.4 | 16.8 | 19.1 | 20.0 | 19.2 | 20.2 | 6.1 |
| | Apr | 19.8 | 16.3 | 19.5 | 21.2 | 20.0 | 19.3 | 9.0 |
| | May | 21.3 | 20.3 | 21.4 | 21.9 | 19.4 | 20.1 | 12.6 |
| | Jun | 22.4 | 21.7 | 23.1 | 23.4 | 22.5 | 21.9 | 16.1 |
| | Jul | 22.6 | 22.6 | 23.7 | 23.6 | 23.2 | 22.3 | 16.9 |
| | Aug | 21.9 | 21.4 | 22.6 | 24.1 | 23.4 | 21.9 | 16.6 |
| | Sep | 21.9 | 21.3 | 22.4 | 22.8 | 21.7 | 21.4 | 14.8 |
| | Oct | 19.7 | 17.9 | 19.7 | 21.1 | 19.5 | 19.9 | 10.3 |
| | Nov | 19.2 | 16.9 | 19.3 | 20.6 | 19.9 | 19.8 | 7.9 |
| | Dec | 18.2 | 15.6 | 17.5 | 19.9 | 19.1 | 19.2 | 4.2 |
| 1983 | Jan | 18.7 | 16.1 | 18.4 | 20.1 | 19.4 | 19.1 | 6.9 |
| | Feb | 17.8 | 14.7 | 17.2 | 19.9 | 18.5 | 18.5 | 1.6 |
| | Mar | 18.9 | 16.2 | 18.5 | 19.9 | 19.2 | 19.6 | 6.4 |
| | Apr | 19.1 | 16.6 | 19.3 | 19.4 | 20.0 | 19.5 | 7.2 |
| | May | 20.0 | 16.5 | 19.5 | 20.2 | 20.1 | 19.4 | 10.5 |

Table 13.3 Seasonal single-room and whole-house average temperatures

| Period | Room | 33 | 35 | 36 | 38 | 39 | 40 | Outside Air |
|---|---|---|---|---|---|---|---|---|
| Winter Nov. 81 to Apr. 82 | liv./din. (S) | 20.6 | 17.4 | 19.7 | 20.6 | | 19.8 | |
| | kitchen (N) | 21.1 | 16.2 | 18.2 | 21.0 | | 18.9 | |
| | hall (N) | 19.8 | 15.6 | 18.3 | 20.4 | | 18.4 | |
| | bed 1 (S) | 18.6 | 15.0 | 18.1 | 19.9 | | 18.5 | |
| | bed 2 (S) | 19.2 | 14.0 | 19.1 | 19.7 | | 19.0 | |
| | bed 3 (N) | 19.4 | 13.1 | 18.7 | 18.6 | | 18.0 | |
| | whole house | 19.7 | 15.5 | 18.6 | 20.1 | | 18.8 | 5.0 |
| Summer May 82 to Sept. 82 | liv./din. (S) | 21.8 | 21.7 | 23.6 | 22.9 | 21.9 | 21.6 | |
| | kitchen (N) | 22.3 | 21.9 | 21.7 | 23.3 | 21.8 | 21.1 | |
| | hall (N) | 21.5 | 21.0 | 21.7 | 23.1 | 20.7 | 20.2 | |
| | bed 1 (S) | 22.0 | 21.7 | 22.5 | 23.5 | 22.4 | 22.8 | |
| | bed 2 (S) | 22.4 | 21.2 | 22.8 | 23.7 | 22.7 | 21.4 | |
| | bed 3 (N) | 22.3 | 20.8 | 22.9 | 22.5 | 22.5 | 21.8 | |
| | whole house | 22.0 | 21.5 | 22.6 | 23.2 | 22.0 | 21.7 | 15.4 |
| Winter Oct. 82 to Apr. 83 | liv./din. (S) | 19.7 | 17.7 | 19.9 | 20.7 | 20.0 | 20.0 | |
| | kitchen (N) | 20.3 | 17.7 | 18.2 | 20.5 | 19.8 | 19.2 | |
| | hall (N) | 18.7 | 16.3 | 18.5 | 20.6 | 18.7 | 18.8 | |
| | bed 1 (S) | 17.9 | 15.4 | 17.9 | 19.7 | 19.0 | 19.9 | |
| | bed 2 (S) | 17.6 | 15.1 | 17.8 | 20.2 | 19.2 | 19.0 | |
| | bed 3 (N) | 18.5 | 15.1 | 18.3 | 19.0 | 19.2 | 18.9 | |
| | whole house | 18.8 | 16.3 | 18.6 | 20.1 | 19.4 | 19.5 | 6.4 |

House 35 is distinctly different from the others. Temperatures are much lower, less uniform around the house, and more influenced by external conditions, particularly the bedrooms, which are either unheated or heated to low temperatures. Living room temperatures are in the range 17-19°C, and kitchen and hall temperatures in the range 15-19°C. Average bedroom temperatures range from 13-17°C during the colder 1981/82 season.

### 13.2.2 Comparison with other field trials

Table 13.4 shows temperatures measured in other field trials, including Pennylands and Neath Hill.

TABLE 13.4 AVERAGE WINTER WHOLE-HOUSE TEMPERATURE FOR VARIOUS FIELD TRIALS

| | Year | Low | Medium | High | No of Houses | Insulation Level | Ref |
|---|---|---|---|---|---|---|---|
| 1 | 48-49 | | 12.2-16.3 | | 36 | Low | 13.1 |
| 2 | 49-50 | | 12.0-17.5 | | 36 | Low | 13.1 |
| 3 | 49-50 | 12.4 | 13.2 | 14.2 | 259 | Low | 13.2 |
| 4 | 69-73 | | 17.0-19.5 | | 60 | Med-High | 13.3 |
| 5 | 71 | | 18.0-19.0 | | 10 | Med-High | 13.4 |
| 6 | 74 | 13.1 | | 14.7 | 25 | Med-High | 13.5 |
| 7 | 77 | | 16.3-16.7 | | 11 | High | 13.6 |
| 8 | 78 | | 15.6 | | 24 | V. High | 13.6 |
| 9 | 77 | 12.7 | 14.6 | 17.1 | 12 | V. High | 13.7 |
| 10 | 81/82 | | 18.9 | | 17 | Med-High | Neath Hill |
| 11 | 81/82 | | 18.4 | | 37 | High | Pennyland 1 |
| 12 | 81/82 | | 18.9 | | 18 | V. High | Pennyland 2 |
| 13 | 82/83 | 16.3 | 18.6 | 20.1 | 6 | V. High | Linford |

The Milton Keynes results are amongst the highest in the historical record and suggests a general tendency to whole house heating. Detailed study of the previous field trials has shown that occupants tend to heat their living rooms to 18-20°C in the evenings and depending on the fuel cost and insulation level extend this to the rest of the house for the rest of the day.

The low seasonal temperatures in examples 8 and 9 are largely the product of heating the living room only. This was probably the result of using on-peak electricity as a fuel.

While the whole-house average temperature of house 35 is low in comparison with the others, table 13.4 suggests that it is perhaps typical for the UK. Clearly, the internal temperatures at Linford are solely a function of the personal preferences of the occupants;

the extra benefit of higher comfort can be taken up if desired (at the expense of further energy savings) or not, as in the case of house 35.

### 13.2.3 Summer averages

These are much the same between houses, ranging from 21.5°C to 23.2°C for the whole house average temperature from May to September (table 13.3). The highest monthly average was 24.7°C for a south-facing bedroom (house 38) during August 1982.

Summer conditions are described in more detail later.

### 13.2.4 Comfort at relevant times

It is a fair assumption that by 8 pm, the occupants will wish to be at a comfortable temperature, equal to the thermostat setting. Living room temperatures at 8 pm throughout the year have therefore been plotted in figure 13.2, together with daily average outside air temperature.

Generally the traces are fairly constant during winter, with most daily fluctuations of the order of 1-2°C. Occasionally there are negative fluctuations of up to 5°C which probably correspond to the occupants being absent for a few days. For houses 33, 38, 39 and 40, the temperatures are remarkably constant throughout the whole period, at about 21°C, with excursions up to 25 or 26°C in summer.

Figure .9 shows data in the same way, for temperatures at 11 pm in the main bedroom. Generally, bedroom temperatures are more strongly related to outside air temperatures. However, during winter periods, the bedroom thermostat maintains fairly repeatable temperatures of 17-20°C for houses 33, 36, 38 and 39. House 40 is somewhat more fluctuating. This is probably due to the occupants' use of the bedroom thermostat as an on/off control to heat the upstairs rooms on demand.

The bedroom temperature for house 35 appears to be strongly related to outside air temperature, suggesting that the bedroom is unheated or the thermostat set to a very low level. The occupants said that their normal thermostat setting was 15°C, which appears to be the case for most of the winter periods, except for the very cold weather during December 1981/January 1982 and February 1983. From discussions with the occupants, it was clear that these relatively low temperatures were purely a matter of choice on their part.

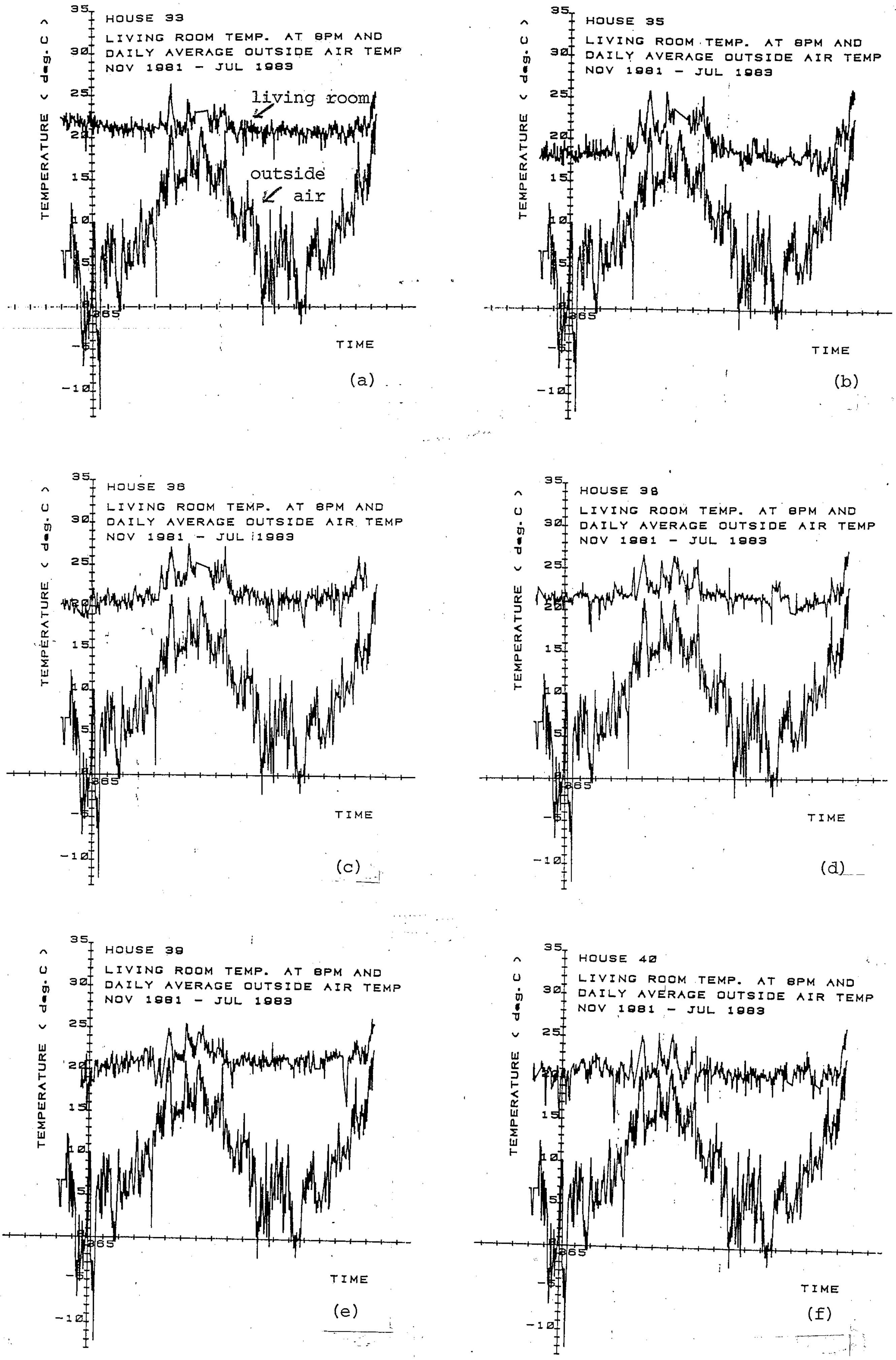



Figure 13.2 Living room temperatures at 8 p.m.

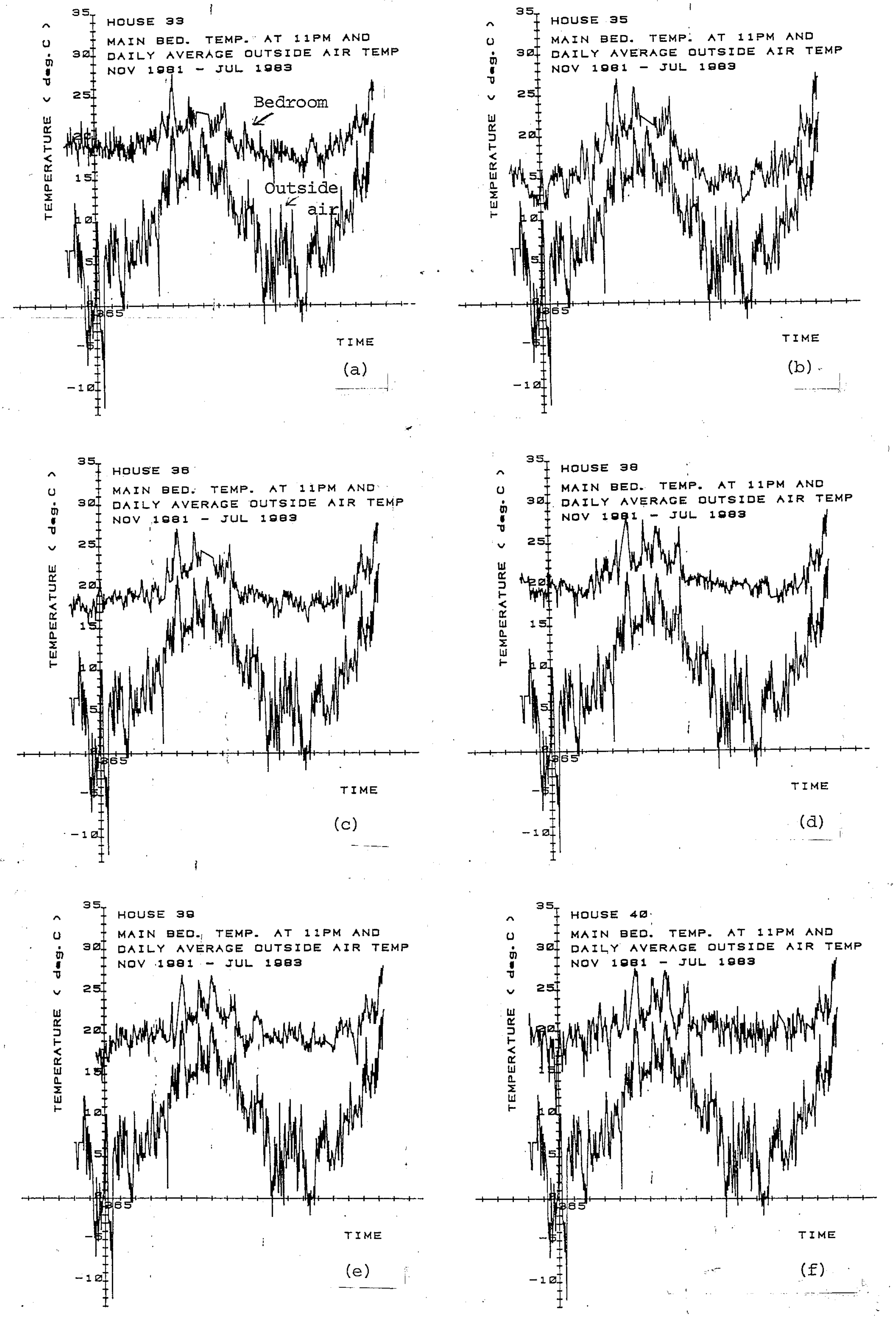



Figure 13.3 Main bedroom temperatures at 11 p.m.

## 13.3 Short-Term Temperature Profiles

When deciding whether they are comfortable or not, the occupants will be strongly influenced by the maxima and minima temperatures, and the rate of temperature change during, say, a 24-hour period, rather than average temperatures.

Examples of hourly temperature profiles during three periods (mild, cold and very cold) are shown for two houses, in figures 13.4-13.6. These two houses (35 and 38) have the lowest and highest temperatures and energy consumptions.

The three weather conditions are:

(i) Mild - outside temperature between 5°C and 10°C.

(ii) Cold - outside temperatures between -4°C and +4°C.

(iii) Very cold - average outside temperature of about -8°C over 3 days, with minimum of -17°C.

Three internal temperatures are shown - living room (south), hall (north) and main bedroom (south).

### 13.3.1 Comfort levels (figures 13.4-13.6)

The temperatures in house 38 show a high level of comfort chosen by the occupant, with the living room thermostat set at about 21°C, and the bedroom at 20°C. The hall temperature very much follows the living room temperature; the remaining rooms are much the same, the house being heated to a very uniform level. For the February period (figure 13.5), the living room thermostat appears to have been raised to 23°C. These temperatures are much the same even for the very cold period during January 1982 (figure 13.6). Clearly, high standards of comfort can be achieved, with whole-house heating, even in the most severe weather conditions that are encountered in the UK.

The temperatures in house 35 are much lower. The living room thermostat is operating consistently at 18°C for all three weather conditions, but the hall and bedroom temperatures show a dependence on outside temperature. For example, the bedroom temperature during heating periods is about 15°C for the mild period, 13°C for the cold period and 12°C for the very cold period.

The corresponding hall temperatures are 16-17°C, 14-15°C and 13-14°C. The relationships between internal and external temperatures are discussed in more detail in chapter 13 (heating system and controls).

The temperatures in this house resemble those expected in a less well insulated house. However, it was clear from discussions with the occupants that this was from personal choice, and not as a result of inadequate heating or for financial reasons. The occupants of all the houses stated that they were able to heat their houses to the temperatures of their choice, and that they were very comfortable.

### 13.3.2 Effect of thermal mass

#### (i) overnight cooling

Overnight temperature decay is limited to 1-2$^{o}$C in mild weather (Figure 13.4), and 3-4$^{o}$C in colder weather (Figure 13.5). It is still only about 3-4$^{o}$C in the extremely cold weather (Figure 13.6), when outside temperatures fell to -17$^{o}$C, due to the heating systems being left on for slightly longer periods.

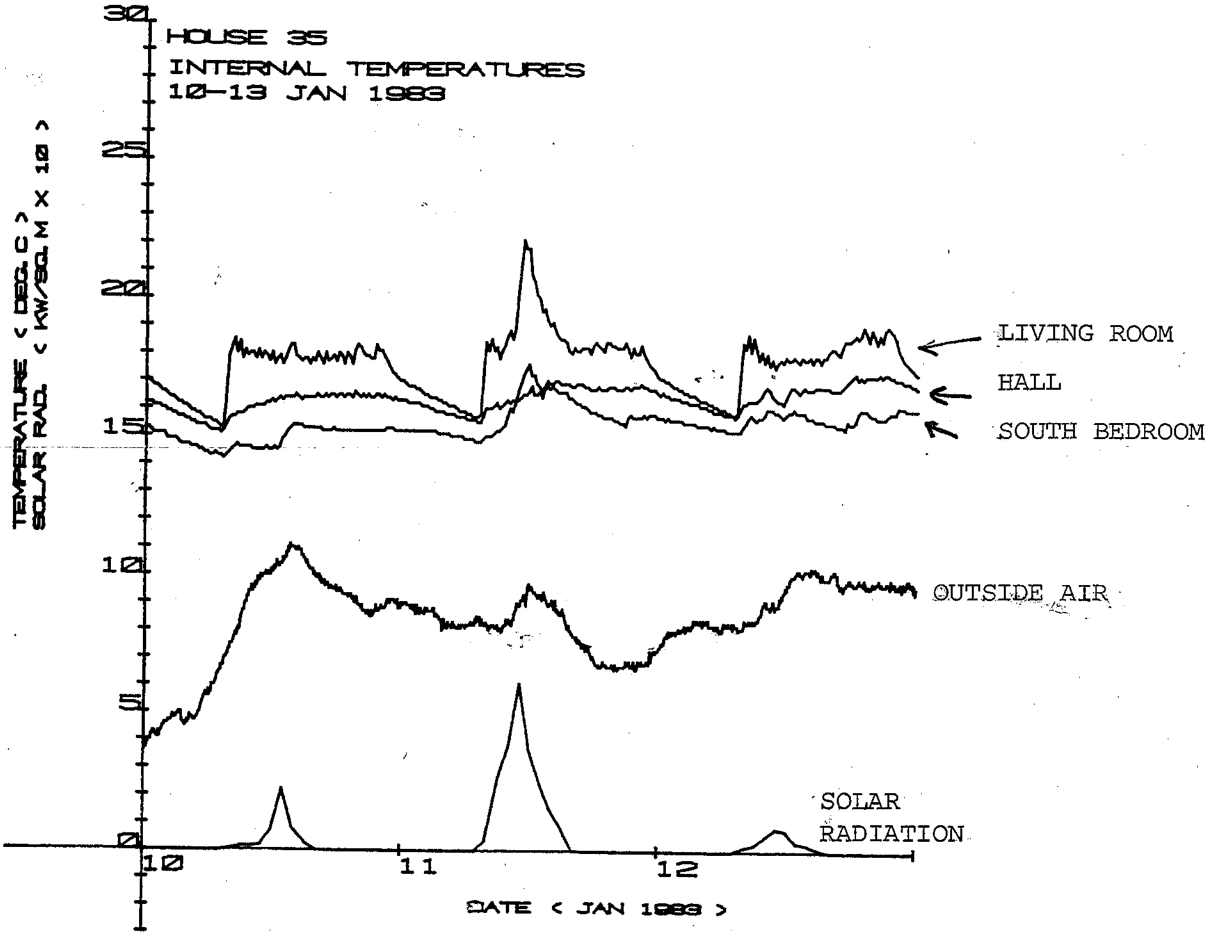
The overnight drop in living room temperature is slightly greater for house 35 than the others. This is probably because of extra heat loss from downstairs to the cooler bedrooms upstairs. Consequently, the rate of temperature decay in the bedrooms is slower that in the other houses.

#### (ii) warm-up

The warm-up rate in house 35 is remarkably fast, resembling that of a timber-frame house, while house 38 appears as might be expected for a high thermal mass house - an initial sharp rise in temperature, followed by a more gradual rise throughout the day as heat is absorbed by the structure. This is partly due to the different starting temperatures involved, but is also due to differences in the way the heating system is operating. This is discussed in chapter 13.

#### (iii) solar gains

The effect of high solar gains can be seen in Figure 13.4 (11th January). Temperatures are raised above the thermostat setting, resulting in the heating system shutting off (not shown) and heat going into storage, which will offset subsequent heat requirements. This is illustrated and discussed in more detail in chapter 10, while the dynamic process of heat flow into thermal storage is discussed in chapter 8.



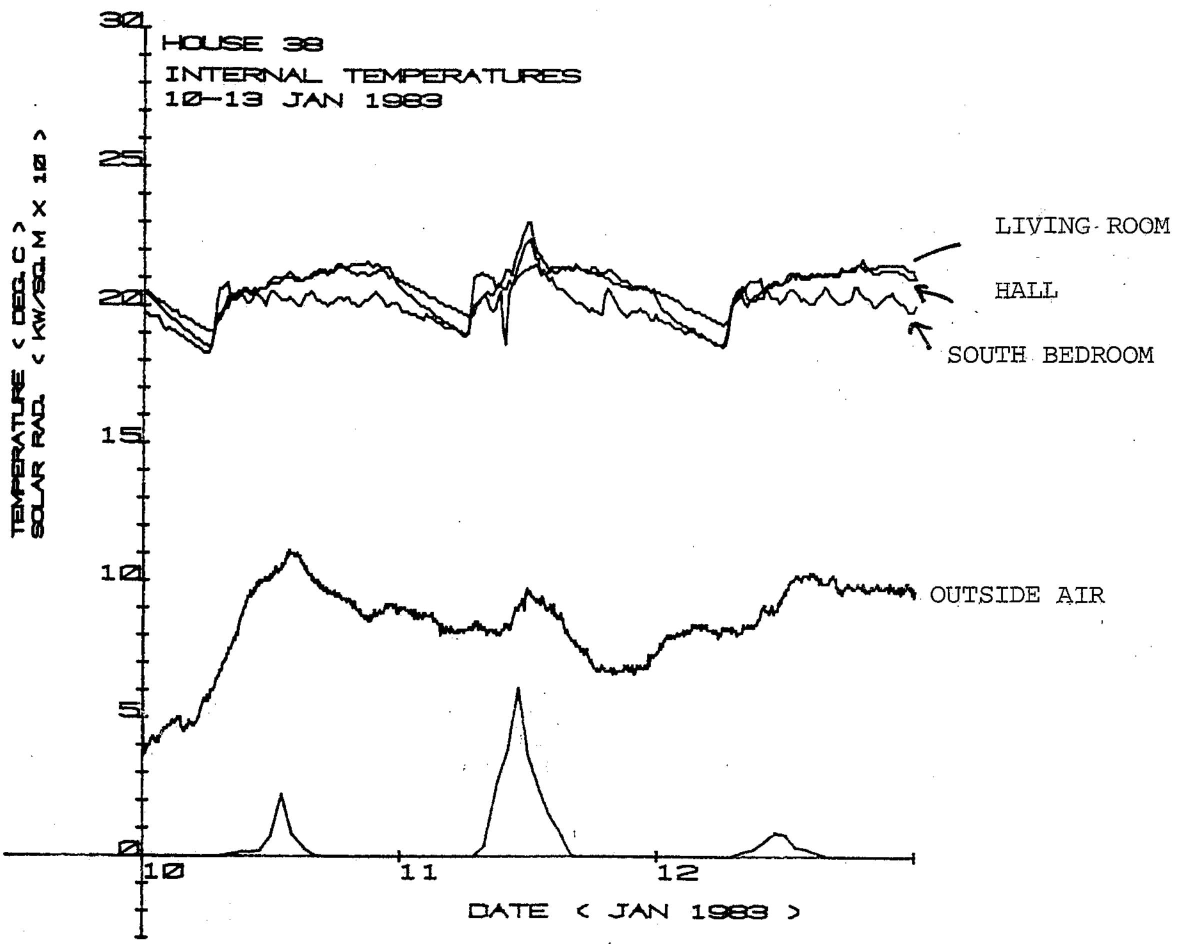
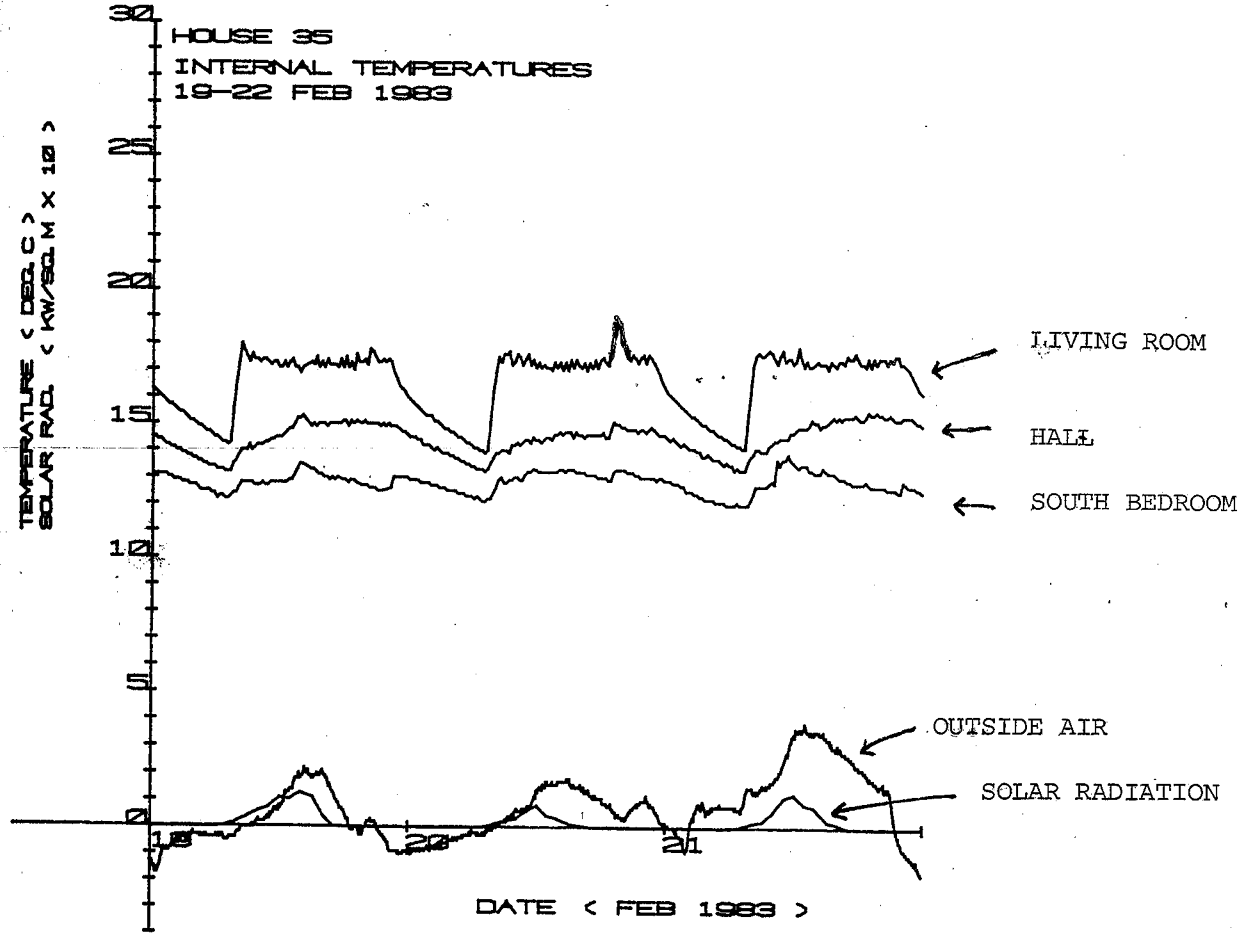




Figure 13.4 Temperature profiles during mild weather



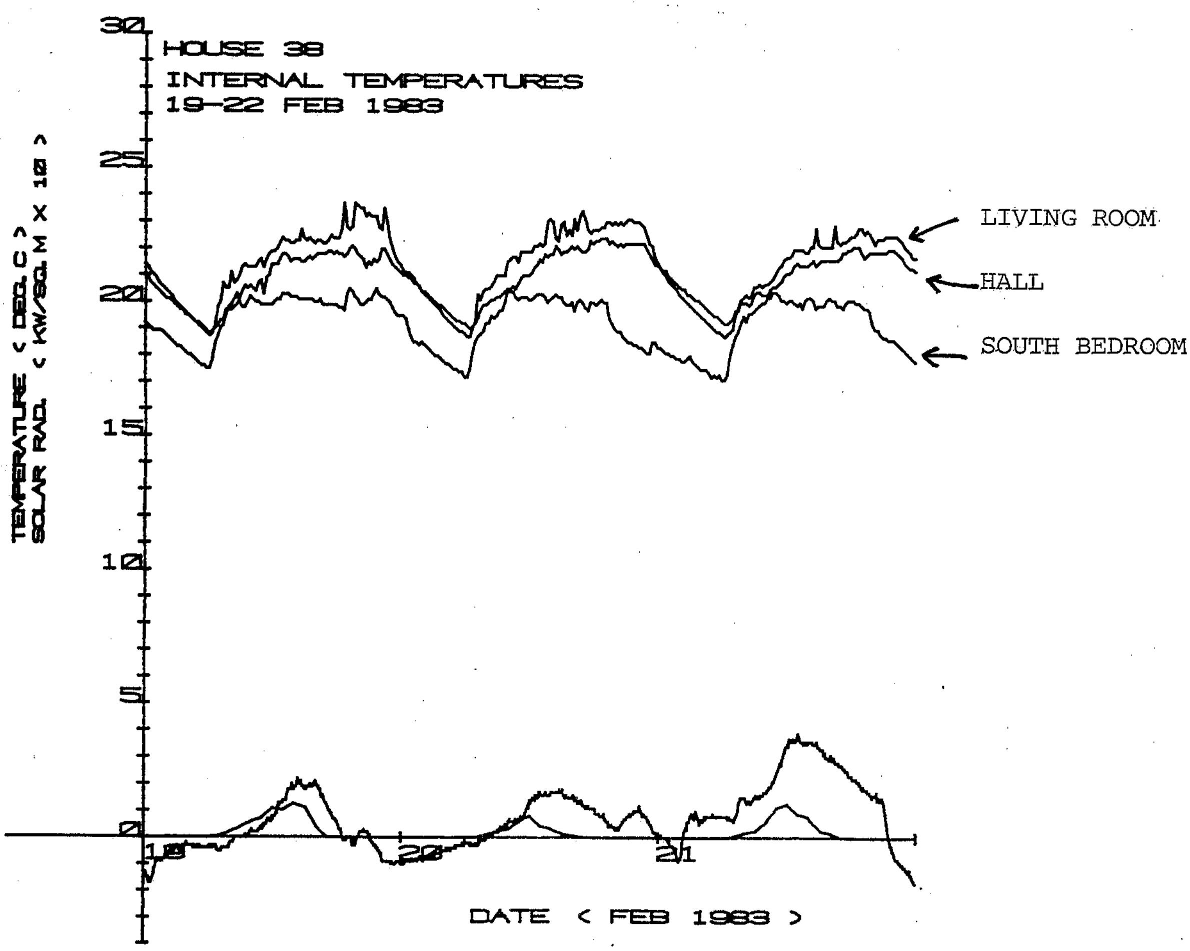
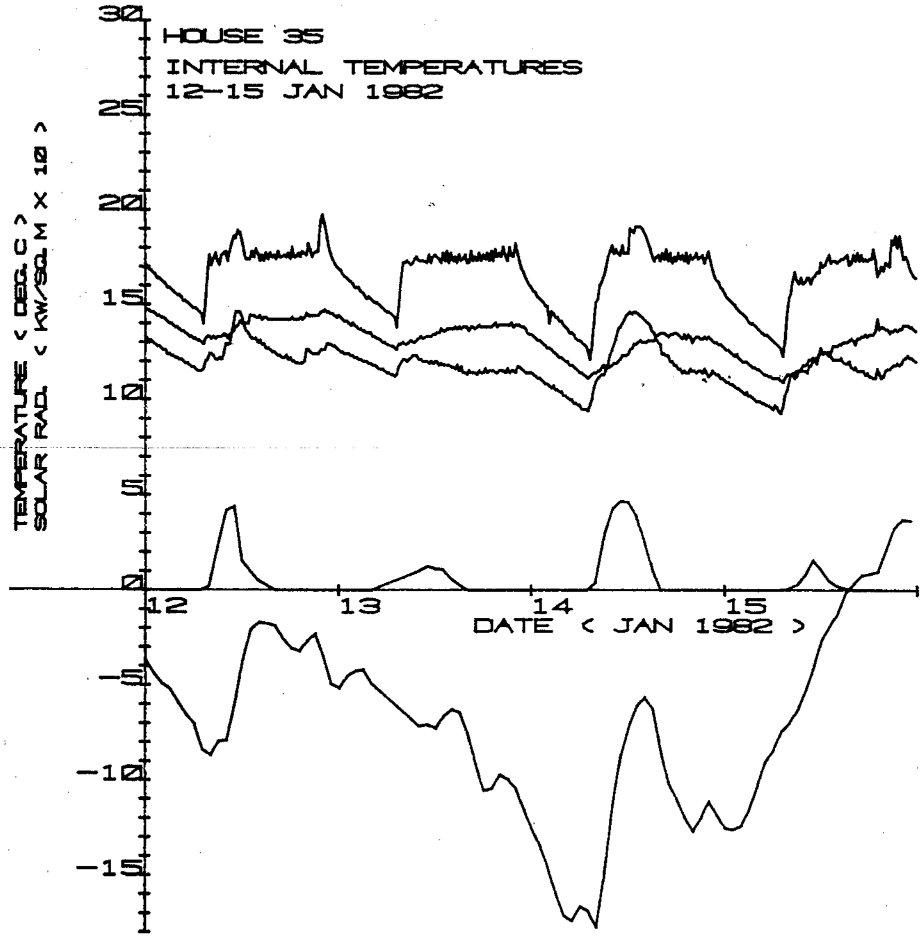




Figure 13.5 Temperature profiles during cold weather



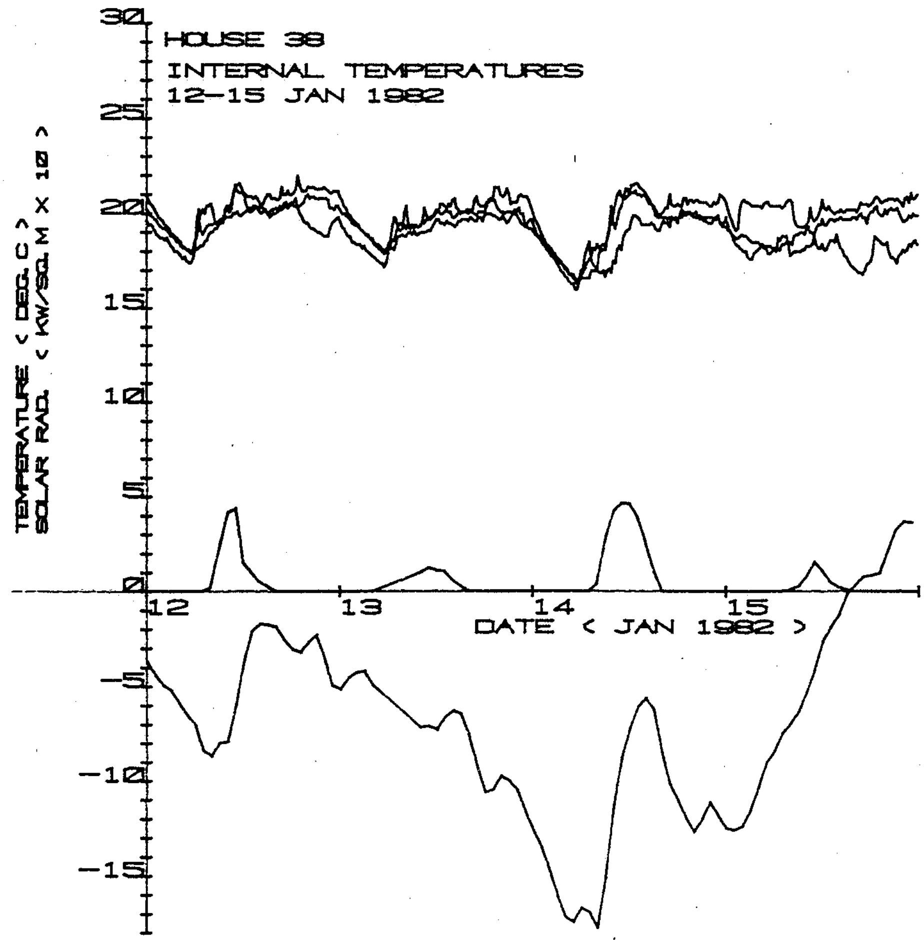




Figure 13.6 Temperature profiles during very cold weather

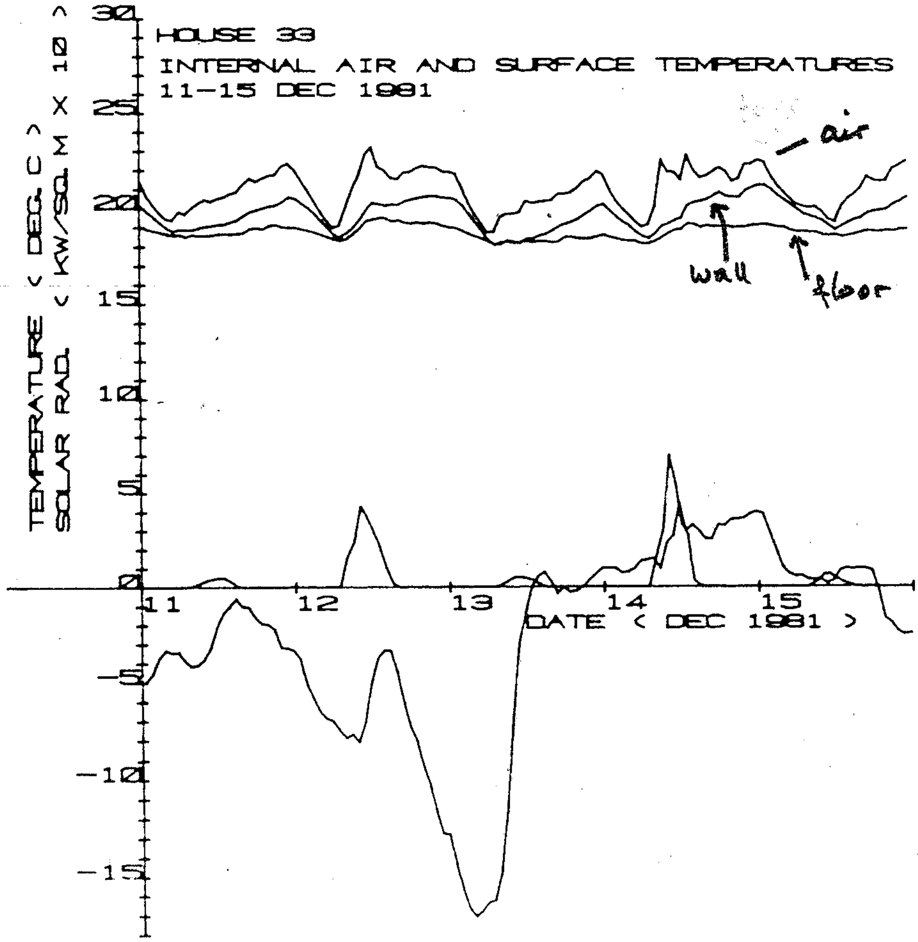



Figure 13.7 Stabilising effect of thermal mass during period with rapidly changing outside air temperature. Shown are the living room air temperature, wall surface and floor surface temperatures for house 33

A further example of the stabilising effect of the thermal mass is seen in Figure 13.7. This is for another very cold period, where the outside temperature changes very rapidly from about $0^{\circ}C$ down to $-17^{\circ}C$ and then up again to $+4^{\circ}C$, in the space of three days.

Plotted in Figure 13.7 are the inside air temperature, the internal surface temperature of an external wall and the concrete floor surface temperature, in the living room of house 33. The floor temperature sensor was positioned just below the plastic tiles laid on the floor slab which in turn were beneath a thick carpet. The degree of fluctuation increases with the degree of associated thermal mass - the floor slab, in contact with the virtually infinite mass of the ground itself, the wall, whose mass consists of the internal dense concrete blockwork, and the air which has very little mass, but which is strongly affected by the behaviour of the surrounding structural temperatures.

A very striking feature of Figure 13.7 is the high repeatability of the underlying temperature profiles despite highly variable outside air temperatures. The only differences from day to day are caused by the high solar gains (12th and 14th), producing more rapid temperature increases during warm-up (i.e. it is "solar-assisted"). These heat inputs are administered internally (i.e. within the insulated shell), and their effect is experienced relatively quickly. Rapid changes in outside temperature, which can be regarded as both positive and negative heat "pulses", have virtually no visible effect on internal temperatures in the short-term, due to the heavy damping effect of the combination of external thermal mass (brickwork), insulation, and internal thermal mass (dense concrete blockwork). This smoothing effect not only produces regular, comfortable and controllable internal conditions, but has the advantage of reducing peak heating requirements. This is discussed in chapter 13.

## 13.4 Full range of comfort conditions

The quality of the internal temperature environment can be appreciated by plotting frequency distributions of hourly temperatures, as in Figures 13.8 and 13.9. These show the range and frequency of living room and bedroom temperatures for all seven houses, during December 1982, for which the average outside air temperature was close to the long-term average for that month.

A perfectly controlled internal environment, with a constant temperature at all times, would have a single column at the thermostat setting. In practice, intermittent heating, the effect of thermal mass, and solar gains will result in deviations below and above the thermostat settings, to produce a range of temperatues as shown. The range itself will depend on the degree of intermittent heating and the damping effect of the thermal mass.

The following features can be seen:

(i) In all cases, for in excess of 70% of the time, the living room temperature was within a 3 deg.C band at the centre of the distributions shown, corresponding approximately to the thermostat setting.

(ii) In one house, the living room temperature never fell below 17°C, in three houses the lower limit was 16°C, in one house it was 15°C and in another it was 14°C.

## 13.5 Summer conditions

A potential problem with any form of passive solar design is that of summer overheating. In the Linford houses, the high level of internal thermal mass is not only useful in storing heat and generally stabilizing temperatures during the heating season, it also stabilizes temperatures during the summer, by absorbing excess heat generated by large solar gains, to reduce temperature swings. The folding blinds on the south windows were also intended as a means of controlling internal temperatures during particularly sunny weather.

To assess the internal comfort conditions during summer, the data has been analysed in two ways: hourly temperatures during several days of particularly hot sunny weather, and frequency distributions of all hourly temperatures over the summer period (June-August).

### 13.5.1 Hourly profiles

Figure 13.10 shows hourly data for four houses, for the period 9-14th July 1983. The weather during this period was considered as heatwave conditions for the UK, with clear skies for several days and external temperatures reaching 31°C.

Shown in Figure 13.10 are the external air temperature, six internal air temperatures (living room, kitchen, hall, two south-facing bedrooms and one north-facing bedroom), south-facing solar radiation, and window openings.

For the first two days, internal temperatures were above the external temperature at the hottest time of the day, by 2-4°C (houses 33,35, 36). This is particularly noticeable for the 10th July, when the external temperature only reached 23°C after peaking at 26°C the day before. The internal temperatures continued to fall very slowly from the 9th, almost unaffected by the slightly cooler, less sunny conditions on the 10th.

The next four days were a succession of very sunny days, with the peak external temperature increasing steadily from 27°C on the 11th, to 31°C on the 14th. For houses 33, 35 and 36, the peak internal temperatures are 1-3°C lower than outside. For house 38, they are about the same or slightly higher than outside.

The effect of the thermal mass can be clearly seen. Very large external temperature swings of up to 17 deg.C are heavily damped inside the house

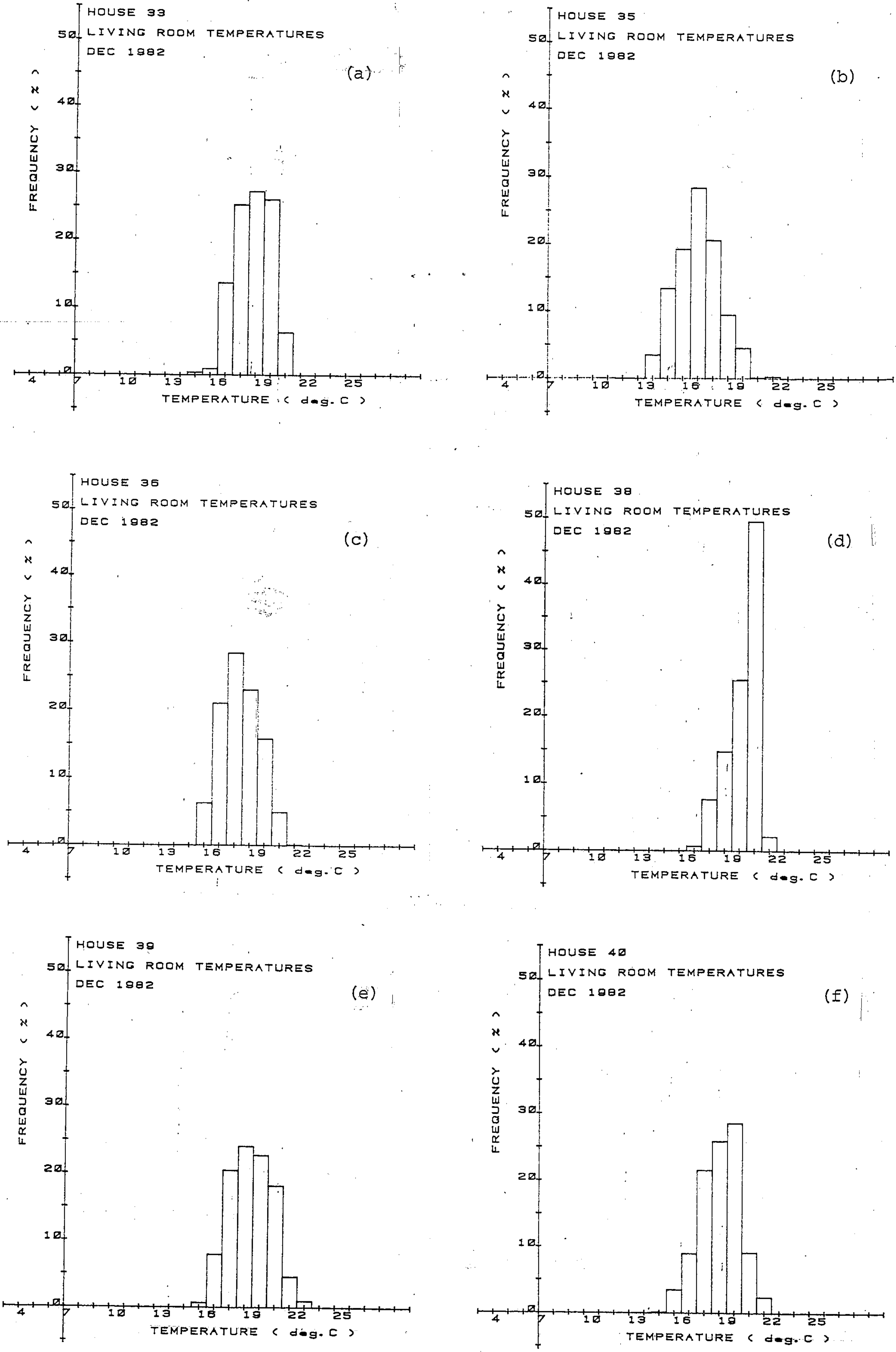



Figure 13.8 Living room temperatures, December 1982

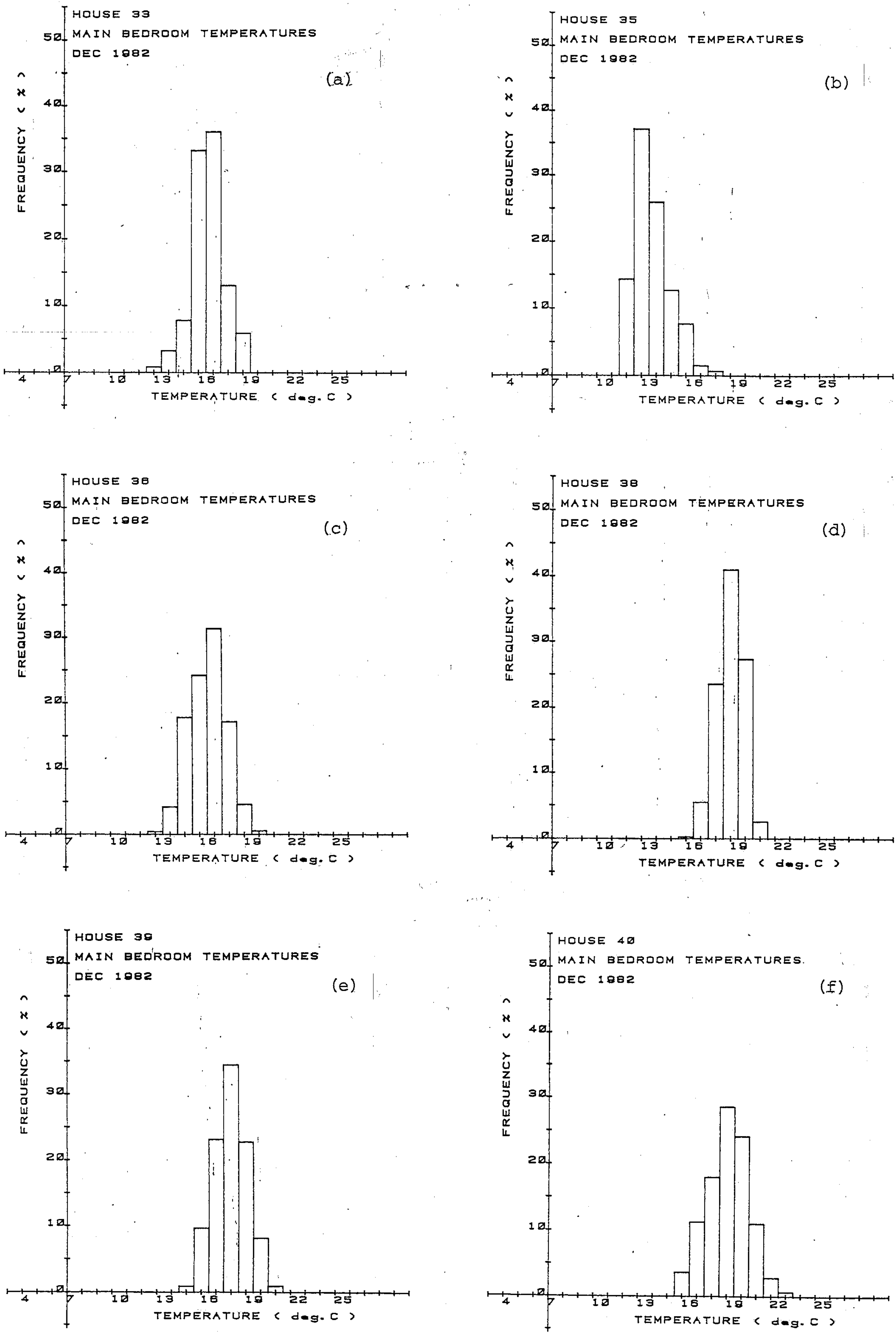



Figure 13.9 Main bedroom temperatures, December 1982

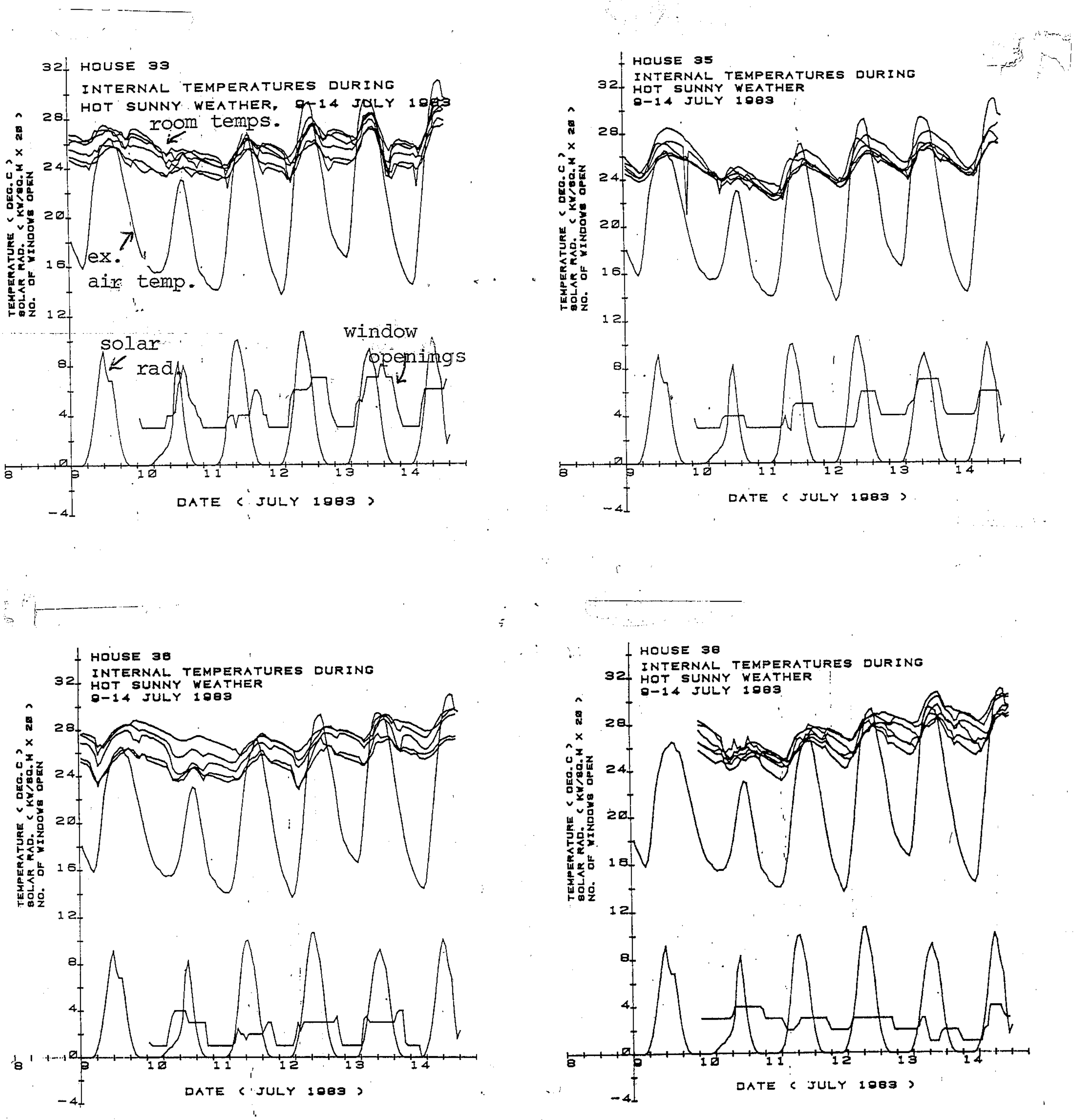



Figure 13.10 Internal temperatures during hot sunny weather

to around 4 deg.C, and the peak internal temperatures are the same as or lower than outside. The overnight temperatures are, of course, much higher than outside, and generally only fall to about 24$^{o}$C by dawn. This is a disadvantage of the thermal mass, in that overnight temperatures only fall slightly from daytime maxima. It may feel hot and stuffy during the night as a result. However, the majority of occupants claimed that this was not a problem to them. Those that were particularly aware of it said that it was an acceptable drawback, given the other low-energy advantages of the house design.

Some effects due to window opening can be seen in Figure 13.10. For houses 33 and 35, there is a "background" of 3 windows open, continuously over the period, with extra windows opened during the day. The pattern is the same for house 36, but at a lower level - only one window is open overnight, increased to 3 or 4 in the day. The pattern is less clear for house 38, and actually appears to decrease on average, as the weather gets hotter.

As a result of the lower levels of window openings in houses 36 and 38, temperatures are slightly higher than 33 and 35, particularly house 38.

The 13th July is particularly interesting. Both houses 33 and 35 have a large number of open windows - 7 during the day, and 3 at night. For house 36, there are a lower number open - 3 windows during the day and only one at night. For house 38 the number is also low, alternating between 1 and 2 during the day and one at night. As a result, temperatures in houses 36 and 38 are 1 or 2$^{o}$C higher during the day and 2 or 3$^{o}$C higher during the night. For house 33, seven windows remain open until about 9 p.m., causing internal temperatures to drop almost as rapidly as outside. After 9 p.m., three windows are closed over a period of about 2 hours, bringing the fall in internal temperatures to a sharp halt, and causing them to increase slightly and then remain constant overnight. This results from the thermal mass releasing stored heat into the cooler internal air.

In contrast, the small number of windows open in house 38 has little effect on the rate of cooling - air temperatures are solely dependant on the rate of cooling of the thermal mass.

This tends to indicate that, mainly, internal air temperatures are dominated by the temperature of the thermal mass, but a significant amount of cooling can still be achieved by opening many windows; however on closing the windows the thermal mass once more takes over to re-stabilize and even increase the temperatures.

### 13.5.2 Full range of summer conditions

Frequency distributions of living room temperatures for six houses over the summer of 1982 are shown in Figure 13.11. It is not possible to show this data for the above average summer of 1983, as monitoring ended in mid-July. However, the 1982 summer was fairly average, and included some very hot weather in June.

There is very little difference between the houses, with the temperature ranging between 20$^{o}$C and 24$^{o}$C for most of the time. Temperatures exceeded 25$^{o}$C for less than 5% of the time (except for house 36 where the figure was 10%), and never exceeded 28$^{o}$C.

Similar frequency distributions for other rooms in the houses were much the same; two examples are shown in Figure 13.12 for the kitchen and main bedroom of house 36.

It can be concluded that summer overheating is not a problem in these houses; the combination of thermal mass, blinds and opening windows can keep internal temperatures below outside air temperature during peak conditions on very hot sunny days. Internal temperatures remain high overnight due to the thermal mass, but this can be alleviated by leaving windows open, and is not perceived as a major problem by the occupants.

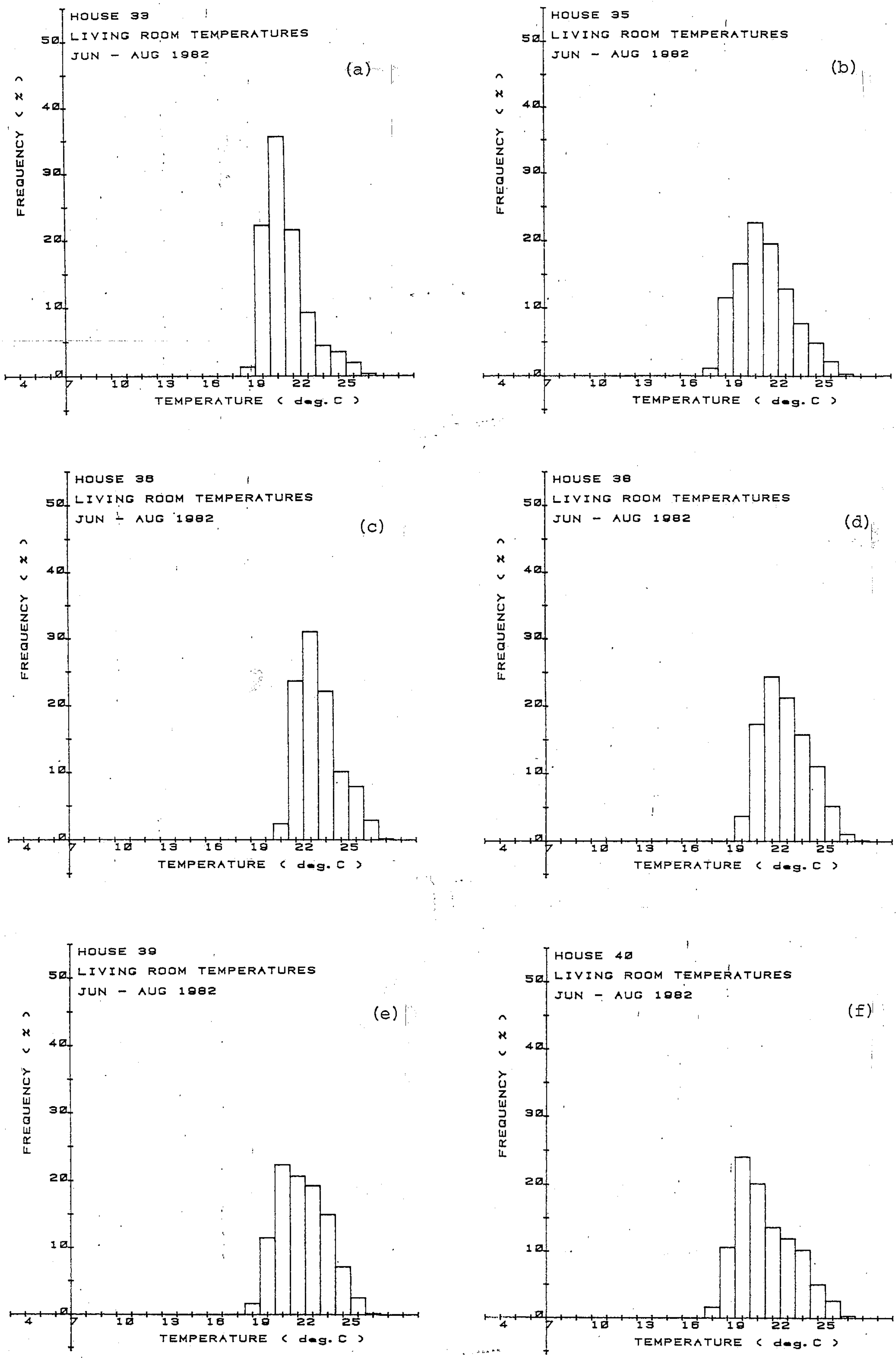
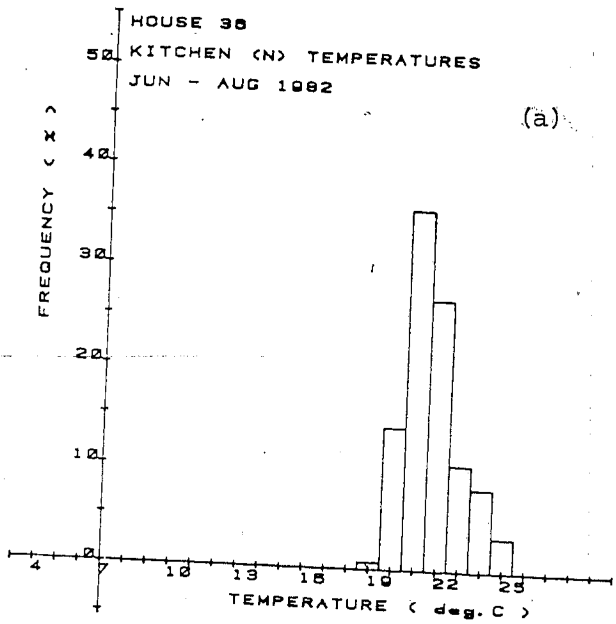



Figure 13.11 Living room temperatures, June-August 1982



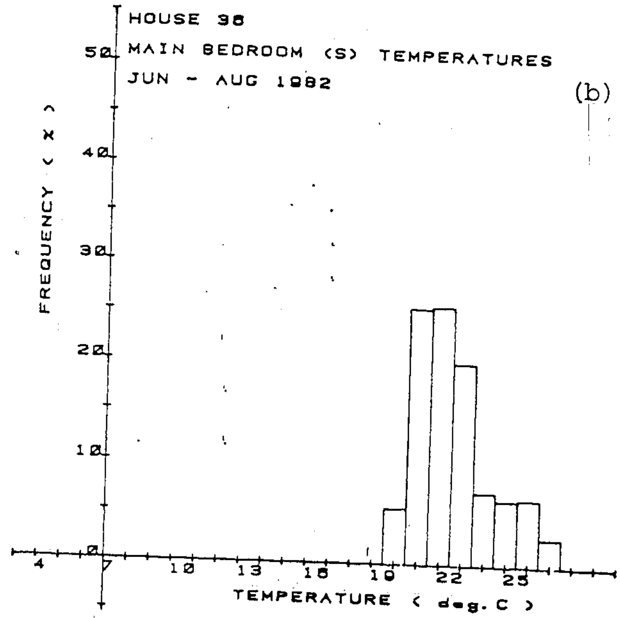




Figure 13.12 Kitchen and main bedroom temperatures, June-August 1982

## Appendix 13.1

### Air temperature and comfort

The perceived warmth of the internal environment depends on a number of factors, such as air temperature, the temperature of the room surfaces, the movement of the air and, in some cases, its humidity. Personal factors include the type of activity and the clothing.

Humphreys (Reference 13.8) concludes from a study of many field trials involving comfort assessment, that the simple air temperature can be used to represent the warmth of an environment, provided that:

(i) The difference between air temperature and mean radiant temperature is small ($<2^\circ C$).

(ii) Air velocity is slight ($<0.2$ m/s).

(iii) Sweat is freely evaporated from the skin.

In the living room of the Linford houses, the mean radiant temperature will be the area-weighted average of the various surface temperatures. The surfaces are:

| | |
|---|---|
| External walls | (~14%) |
| Windows | (~14%) |
| Internal walls, ceiling and floor | (~72%) |

Surface temperatures were measured for the inside surface of an external wall and the floor. A sample of these measurements are shown in Figure A13.1, together with inside and outside air temperatures, for the period 11-15th December 1981. This was an interesting few days, as the outside air temperature fell to $-17^\circ C$ over two days, rising rapidly to just above $0^\circ C$ in 12 hours.

The wall temperature is between only 0 and 2.5 deg.C cooler than the room air temperature, and the floor temperature between 0.5 and 3.5 deg.C cooler. For the whole month of December 1981, the wall surface was 1.2 deg.C cooler than the air, and the floor 1.9 deg.C cooler. The floor temperature was measured just beneath the surface of the cast concrete slab. Above this was a 1/8 inch layer of plastic tiles, and in all houses but one, a thick carpet had been laid over the tiles. Therefore, the actual temperature of the carpet surface is likely to be virtually identical to the air temperature. It can also be assumed that the ceiling and internal partition walls will be at or very close to the air temperature.

The surface temperature of the windows can be estimated from the U value (2.8 $W/m^2\,^\circ C$), as follows:

$$\frac{Ts-To}{Ta-To} = \frac{R-Rs}{R}$$

therefore $T_s = \frac{R-Rs}{R}(Ta-To) + To$

where $T_s$ = surface temperature of window

R = total thermal resistance of window

Rs = inside surface resistance

Ta = inside air temperature

To = outside air temperature

as the U value, $U = \frac{1}{R}$, then:

$$T_s = (1-U.R_s)(Ta-To) + To$$

For December 1981, $T_s \simeq 15^{o}C$

Using the temperature for the windows, the measured average wall surface temperature, the air temperature in place of the floor, ceiling and partition wall temperatures, and a surface resistance $R_s$ of 0.1 W/m $^{o}C$, the mean radiant temperature is approximately 19.6$^{o}$C, compared with the air temperature of 20.6$^{o}$C for December 1981. This difference is less than the maximum stated by Humphreys as a condition for using air temperature to assess comfort.

There is reason to assume that mean radiant temperatures will be even closer to the air temperature, as:

(i) occupants will almost certainly close curtains at night, increasing the effective radiant temperature of the window area.

(ii) no account is made for absorption of solar radiation into the internal structure thereby increasing their surface temperatures.

(iii) no account is made for the radiant effect of the radiators whose temperature will be about 70$^{o}$C with the heating on.

Air velocities were not measured, but as the houses were well sealed (Chapter 9), they are likely to be low. Thus it is justified in using air temperatures to represent comfort.

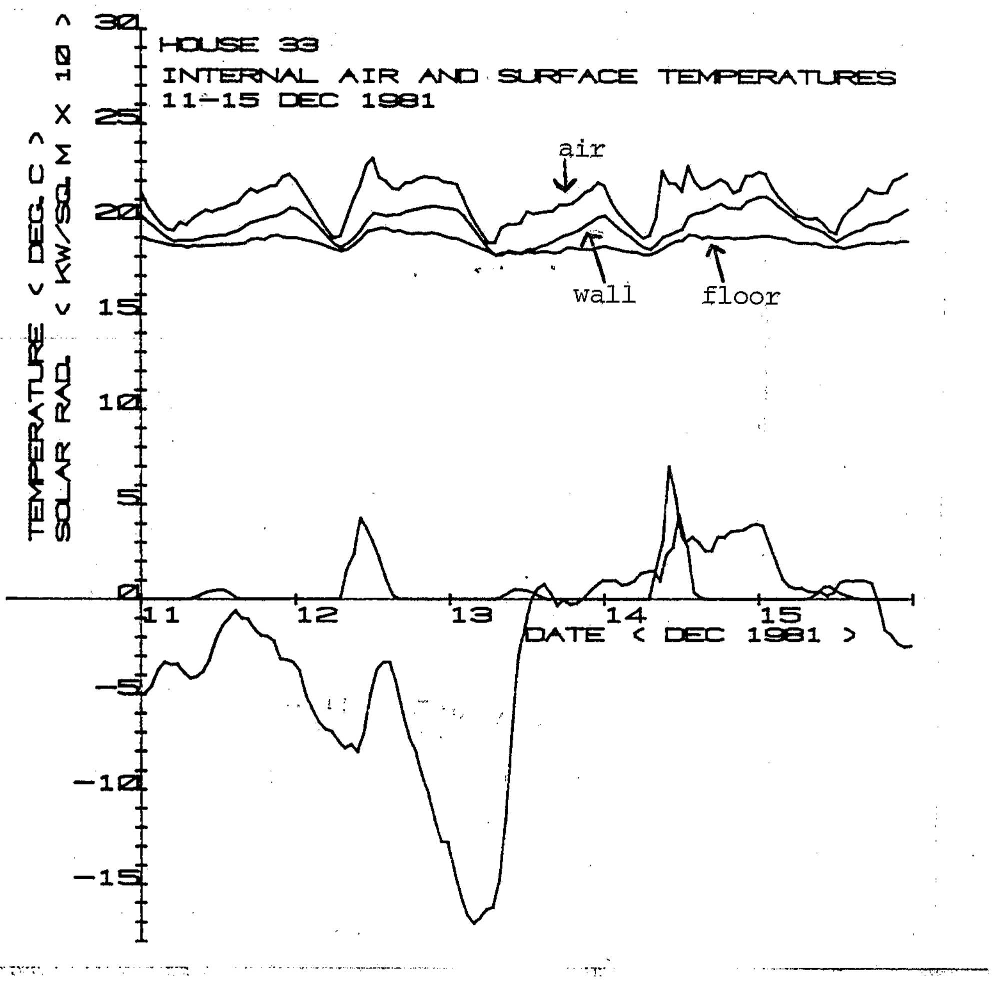



Figure A13.1 Internal air temperature, wall surface and floor surface temperatures in the living room of house 33

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# 14. HEATING SYSTEMS & CONTROLS

CONTENTS



This chapter outlines the approach to the design of the heating system and controls, describes the design itself, and analyses the performance of the system as a whole and some components such as the boiler and space heating control system.

# 14. HEATING SYSTEM AND CONTROLS

## 14.1 Design approach

As the houses were built privately, the heating system was designed and specified in detail by one of the developer's subcontractors in the normal way. However, the designer was given an outline specification to work to, plus the best estimates available for the house heat loss characteristics.

The outline specification required:

(i) the use of a low thermal capacity balanced flue gas boiler.

(ii) separate circulation and thermostatic control for upstairs and downstairs heating, using motorised valves and a single pump.

(iii) thermostatic radiator valves on every radiator except those in the same room as wall thermostats (lounge and main bedroom).

The system as installed is shown diagrammatically in Figure 14.1. Also shown are the positions of the heat meters.

### 14.1.1 System sizing

The estimates for the house heat loss characteristics at the design stage were:

| Element | U value $W/m^2\,^oC$ |
|---|---|
| Walls | 0.3 |
| Floor | 0.5 |
| Roof | 0.2 |
| Windows | 2.5 |
| Doors | 3.0 |
| Ventilation | 1 ac/hr |

The exact sizing procedure is not known, but is likely to have been based on calculation of individual room heating requirements assuming standard temperatures of:

| | |
|---|---|
| Living room | $21^oC$ |
| Kitchen | $18^oC$ |
| Bedrooms | $16^oC$ |
| Outside | $-1^oC$ |

The normal practice would be to calculate nominal radiator sizes for each room in turn, including heat losses to adjacent rooms (but ignoring heat gains from adjacent rooms), and add 10-20% to allow for warm-up conditions. If this is done, the total nominal requirement is 4.9 kW, rising to 5.9 kW on adding 20%. The total output of the radiators installed is 7.2 kW. It would appear, therefore, that a further 20% was added as a safety margin due to uncertainty in the performance of the house design. This is not an unreasonable precaution given the relative unfamiliarity at that time, with the performance of highly insulated passive solar houses, such as those at Linford. Additionally, calculated radiator sizes in small rooms such as the w.c., shower and bathroom are as little as 150 W. As it would have been difficult to specify radiators this small, they have been considerably over-sized. The total output of 7.2 kW compares with the house design heat loss (-1$^{o}$C) of about 4.6 kW.

Table 14.1 lists the radiator sizes and outputs, and Figure 14.2 shows their positions in the house. As windows were double glazed, it was not necessary to position radiators beneath windows as is common practice for single glazing. As a result, most radiators could be positioned on internal partition walls, preventing unnecessary heat loss through external walls.

Adding 3 kW hot water allowance to 7.2 kW gives a nominal boiler size of 10.2 kW.

In practice a 17.6 kW boiler was installed, which would appear to be considerably over-sized. This is because the designer was required to specify a low thermal capacity boiler, and at that time (early 1980) the choice was limited to two boilers, both manufactured by Chaffoteaux Ltd. The smaller model (Corvec Miniflame) had a fixed output of 8 kW, and the larger model (Corvec Maxiflame) had a variable output (set by the gas pressure) of between 11.7 kW and 17.6 kW. This boiler was installed, but it would seem that the gas pressure setting was left at its maximum, as set by the manufacturers at the factory.

As the data presented in this chapter shows, the over-capacity is taken up by the hot water cylinder, where heat inputs can be as high as 8-9 kW. This gives very fast hot water recovery times but is clearly not essential, and the boiler size could be considerably reduced. The over-capacity on the radiator sizes is more beneficial, but the data suggests that their output could be reduced, leading to a further reduction in the boiler size.

### 14.1.2 Controls

To enable more flexible control than a conventional single thermostat system, separate circulation was specified for upstairs and downstairs, each zone having separate wall thermostats and time clocks. The thermostats were positioned in the lounge and main bedroom. In practice, however, the upstairs time clock was omitted and the system operated off a single time clock. Each thermostat, plus the hot water cylinder thermostat, operated a motorised valve thus enabling only one pump to be used (Figure 14.1).

For further control, thermostatic radiator valves (TRV's) were fitted to each radiator except those in the living room and the main bedroom where the wall thermostats were situated. These were excluded to avoid a situation whereby the TRV could turn off the radiator before the wall thermostat was satisfied; the system would then continue pumping, with no way for it to turn off.

An alternative arrangement using TRV's on all radiators with no wall thermostats was considered, but rejected on the grounds that at some stage all radiators might be turned off leaving the boiler to short-cycle on its own output thermostat, losing heat via the flue.

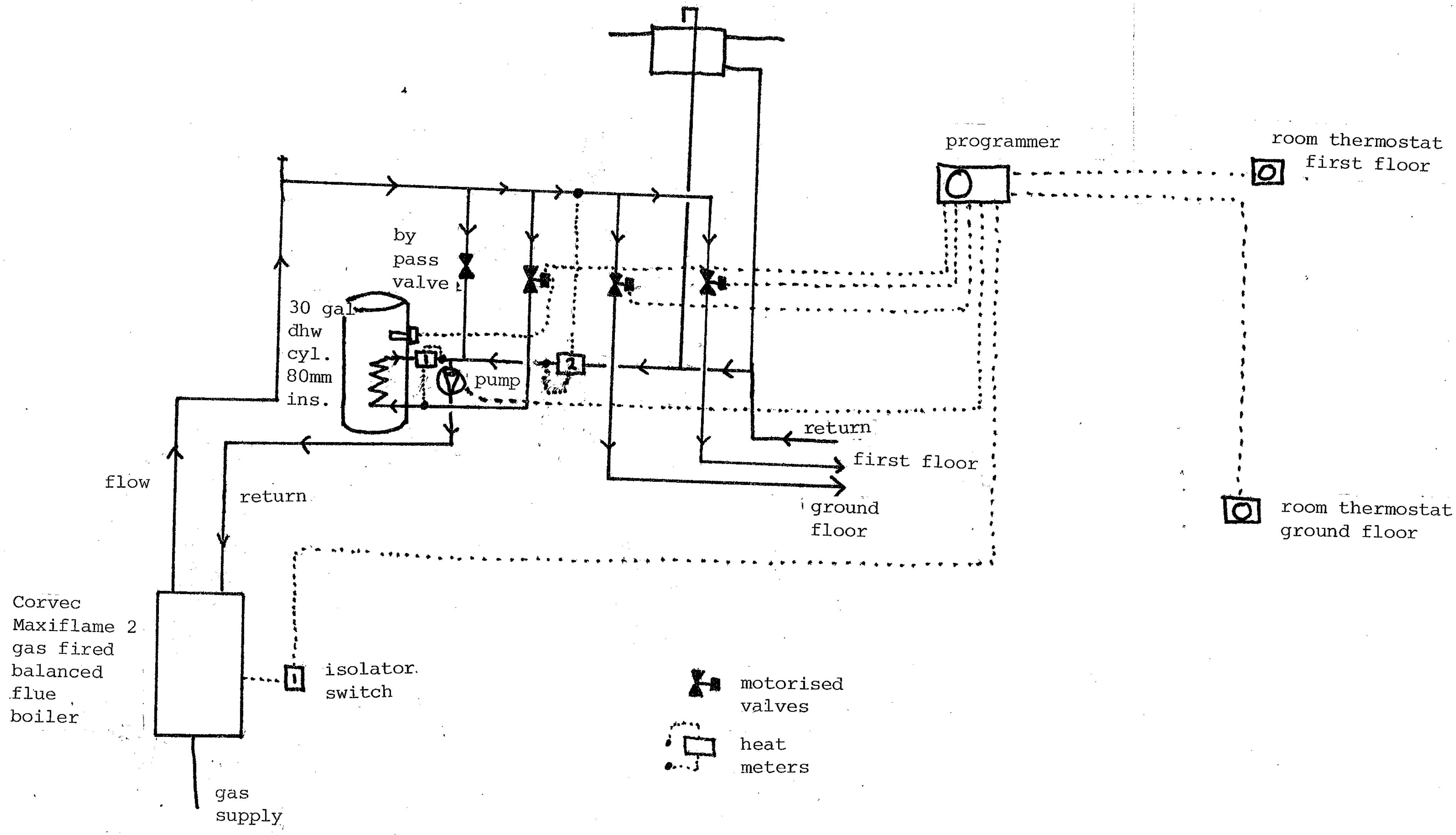



Figure 14.1 Heating system - diagrammatic

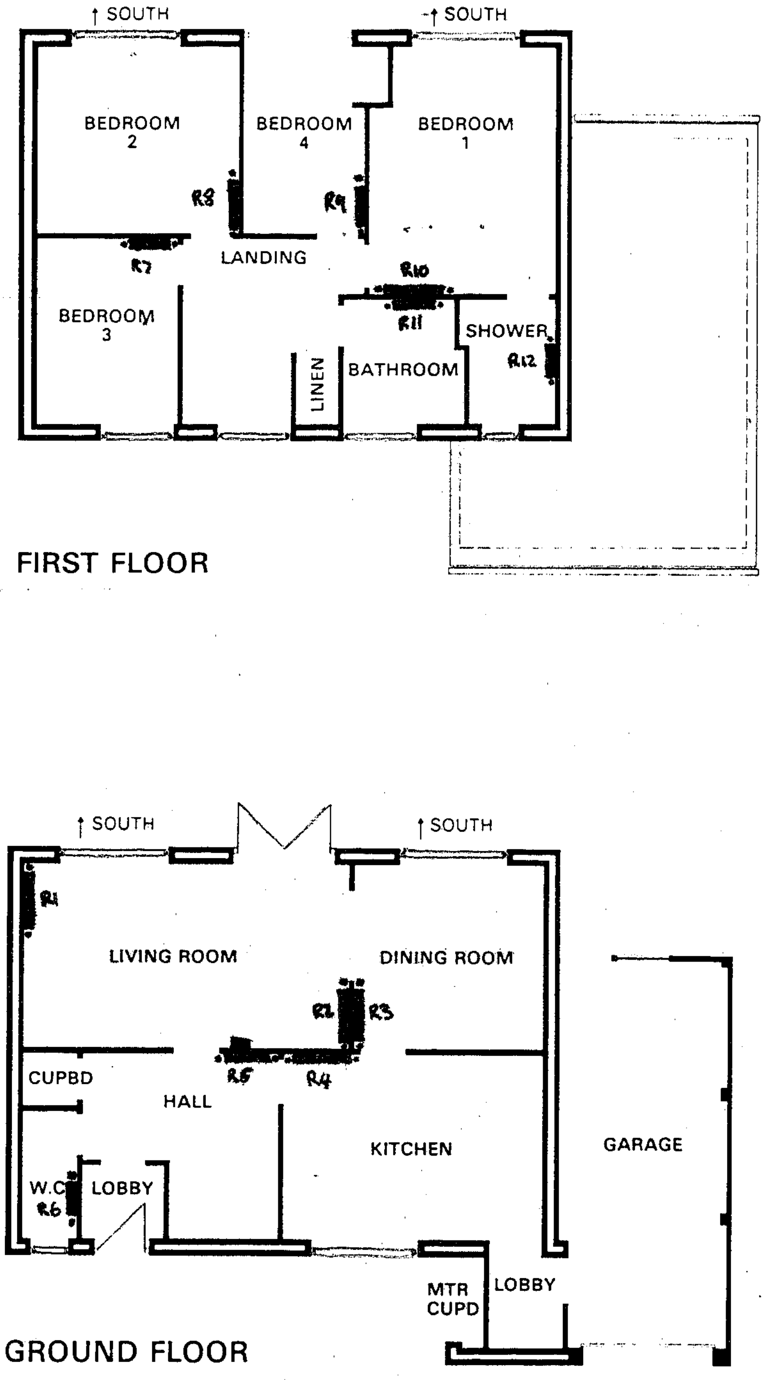



Figure 14.2 Most radiators are positioned on internal partition walls

Table 14.1 Radiator sizes and outputs

| Radiator/Room | Room heat loss | Radiator output (kW) | |
|---|---|---|---|
| R1 living room | ) | 0.962 | |
| | ) 1.137 | | |
| R2 living room | ) | 0.604 | Downstairs output = 4.606 kW |
| R3 dining room | 0.653 | 0.962 | |
| R4 kitchen | 0.671 | 0.906 | |
| R5 hall | 0.555 | 0.962 | |
| R6 w.c. | 0.104 | 0.210 | |
| R7 bedroom 3 | 0.289 | 0.372 | |
| R8 bedroom 2 | 0.455 | 0.496 | Upstairs output = 2.562 kW |
| R9 bedroom 4 | 0.317 | 0.372 | |
| R10 bedroom 1 | 0.507 | 0.744 | |
| R11 bathroom | 0.159 | 0.289 | |
| R12 shower | 0.121 | 0.289 | |
| | | 7.168 | |

The hybrid system installed was recommended by British Gas as a suitable combination of individual room control and efficient operation. However, the inclusion of the extra time clock for upstairs heating would be a further improvement.

It was appreciated at the design stage that there could be situations when direct solar gains in the south rooms would cause both thermostats to turn off the heating system completely, leaving the north rooms below the required temperatures. Occurrences of this have been identified in the data, but it is considered only a minor problem.

## 14.3 Thermal response of house and heating system

Figure 14.3 shows examples of the operation of the heating system and the resulting temperature response of the houses. Two houses are shown, representing lowest and highest internal temperatures, for two weather conditions: typically cold (between -2$^{o}$C and +2$^{o}$C), and extremely cold (between -5$^{o}$C and -17$^{o}$C). For each example the following quantities are plotted:

| | |
|---|---|
| Living room air temperature | (15 min. values) |
| Hall air temperature | (15 min. values) |
| Main bedroom air temperature | (15 min. values) |
| Outside air temperature | (hourly averages) |
| South-facing solar radiation | (hourly averages) |
| | |
| Boiler output for space heating | (15 min. values) |

### 14.3.1 Warm-up rate

The two houses shown have distinctly different temperature levels. In house 35 the living room thermostat is set at 17-18$^{o}$C, and the temperature rises to the set-point very quickly. The bedroom thermostat is set much lower at 12-13$^{o}$C, but there appears to be some manual intervention on the 22nd December (Figure 14.3a). The hall radiator would appear to be off, as the temperature curve rises only very slowly.

In house 38, where all rooms are heated to much the same temperature (see Chapter 13), the living room thermostat is set at about 21$^{o}$C and the bedroom at about 20$^{o}$C. The warm-up rate for the 22nd December (Figure 14.3b) when the outside temperature was about 0$^{o}$C, is also fast - thermostat levels are reached within 2 or 3 hours. The hall temperature follows the other two, indicating that the radiator is fully on.

Even for the extremely cold weather of 13-14th January 1982 when outside temperatures fell to -17$^{o}$C, the warm-up rates are adequate. In house 35, the living room temperature rises as fast as for the previous example, reaching set-point within one hour. For house 38, the time to reach set-

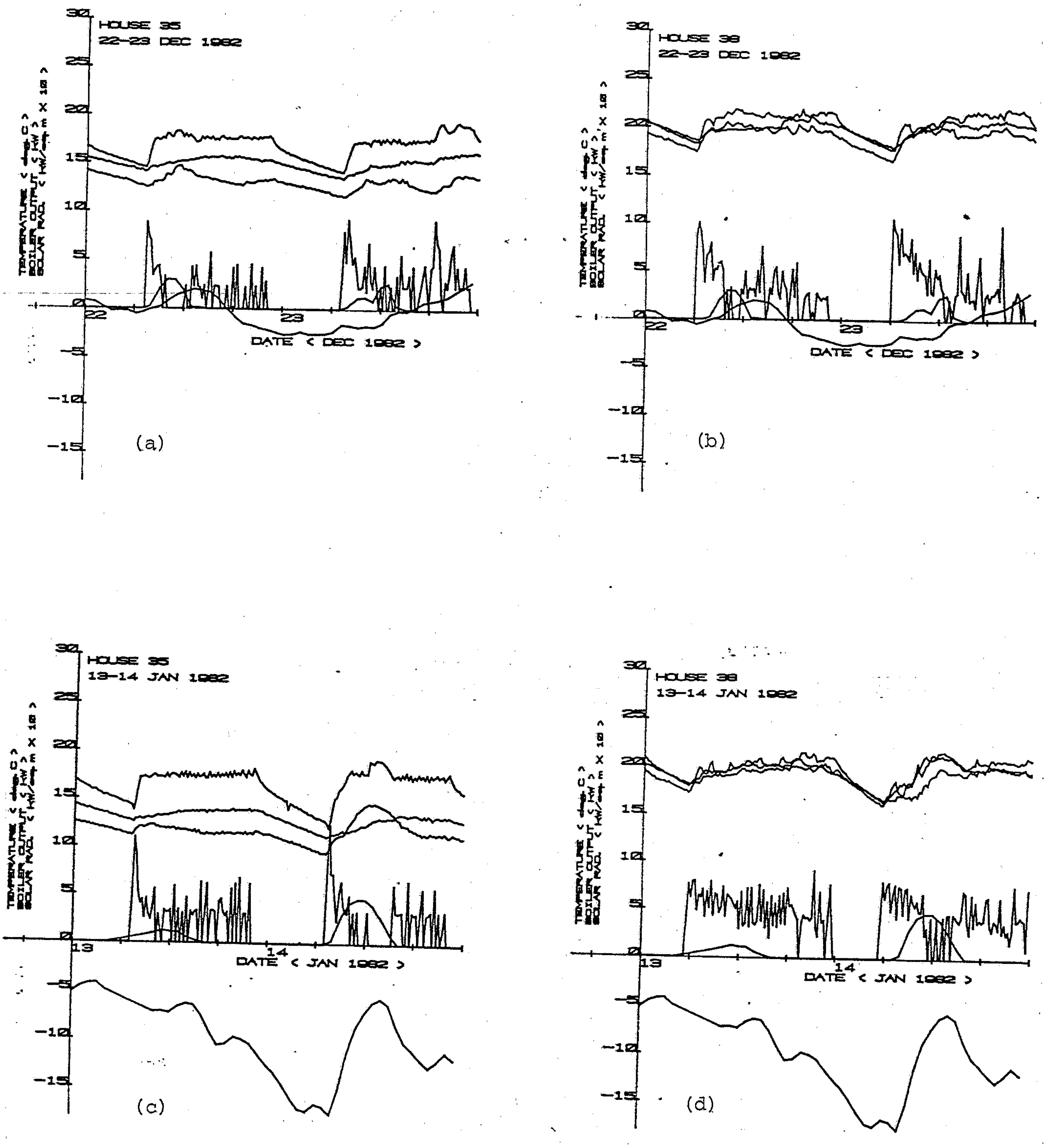



Figure 14.3 Thermal response to house and heating system for typical cold conditions (a and b), and extremely cold conditions (c and d)

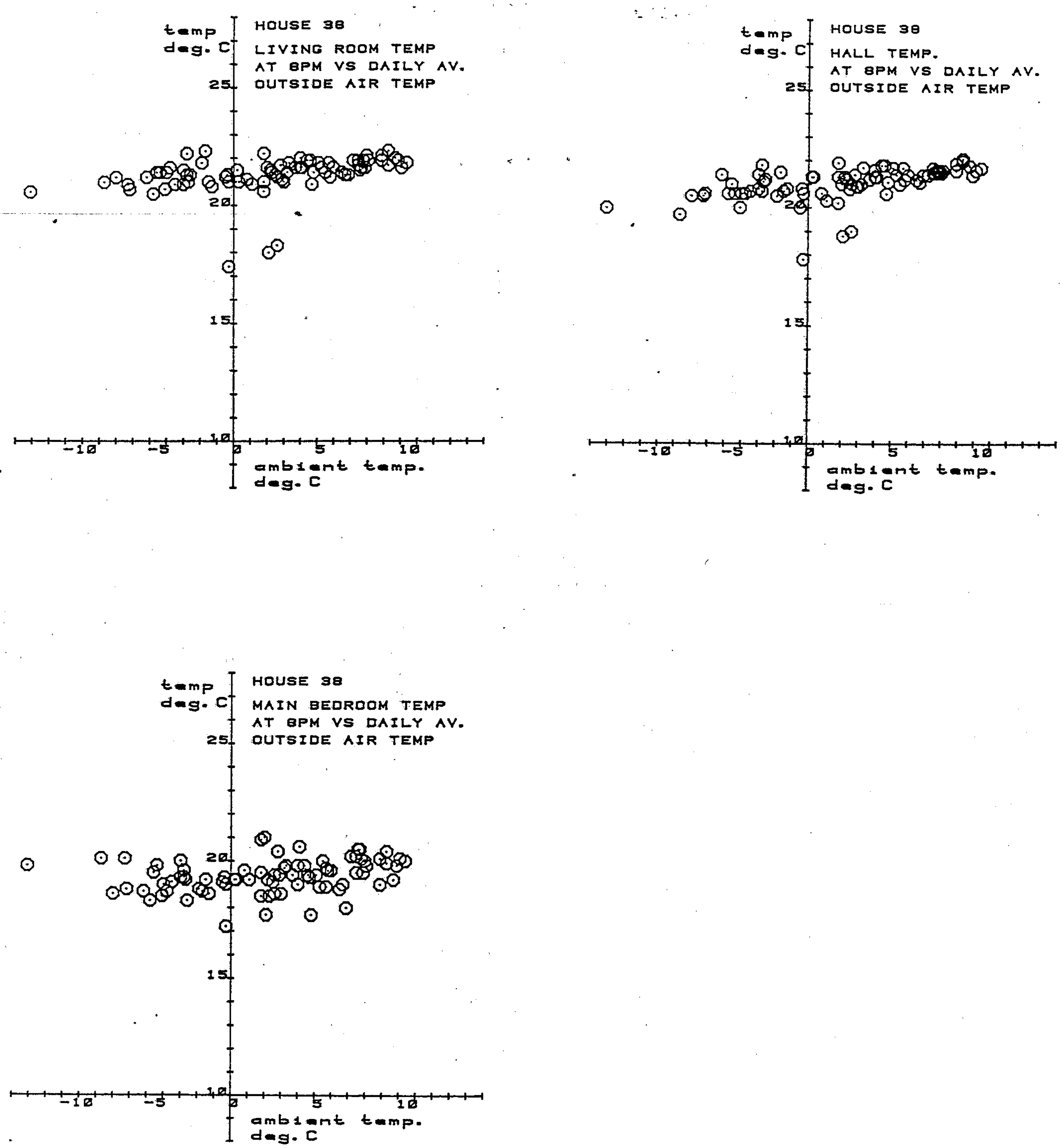



Figure 14.4 Room temperatures at 8 p.m. correlated with daily average outside air temperature. There is very little correlation, and high comfort conditions are maintained over a wide range of external temperatures.

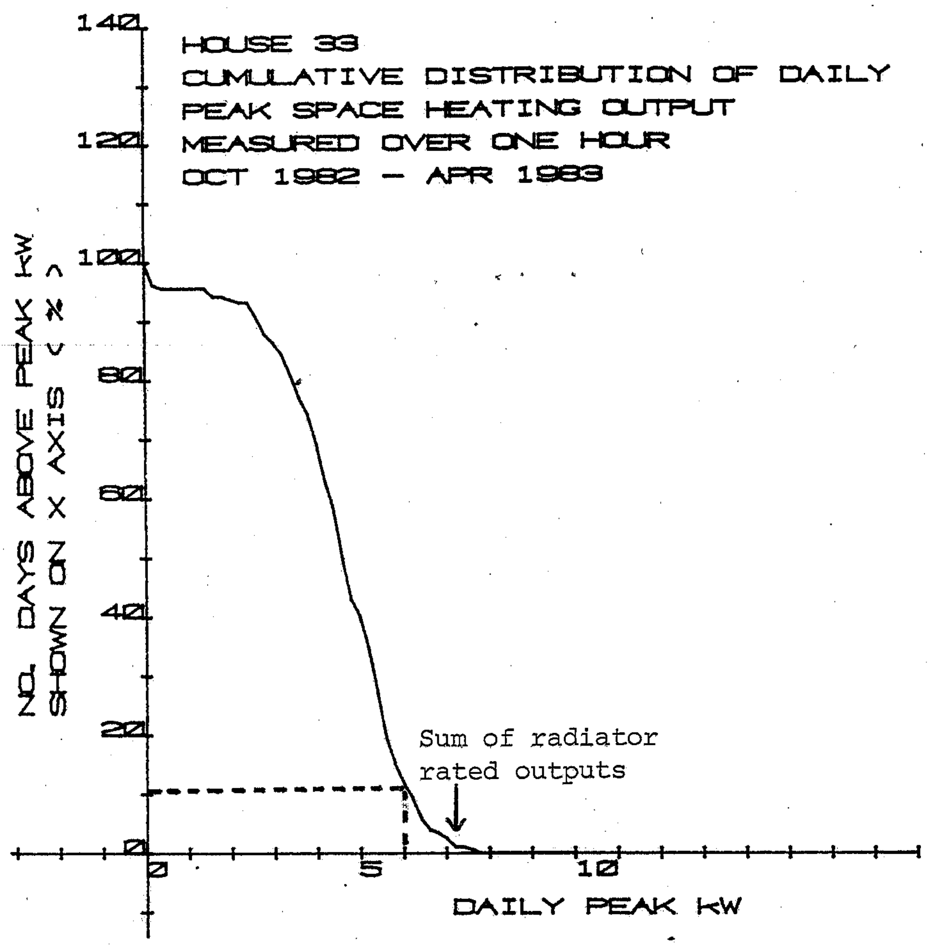
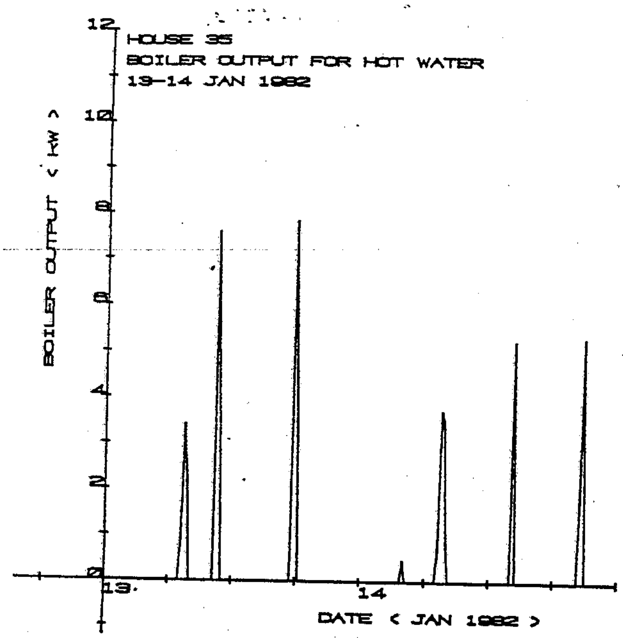



Figure 14.5 A total of 7.2 kW radiator output is just enough to cover the peak heating requirement (over 1 hour) for all days in the heating season. If the radiators were reduced by 17% to 6 kW, the hourly peak heating requirement would be met for 90% of the days in the heating season.



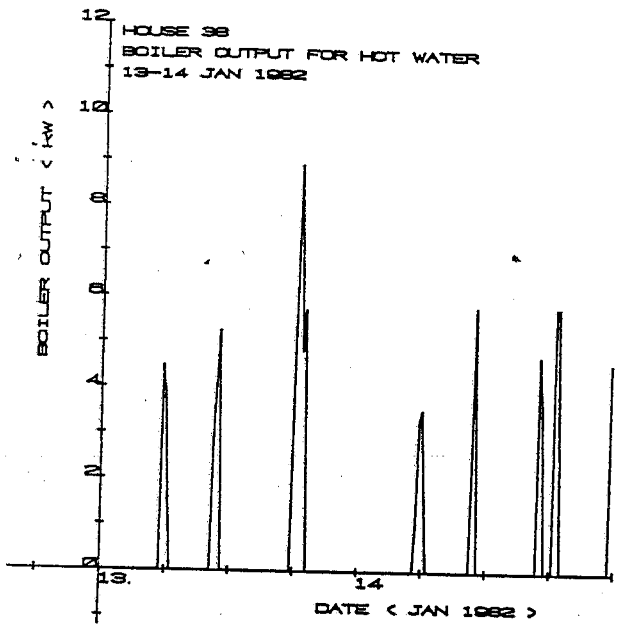




Figure 14.6 The boiler is operating in short, sharp bursts up to 9 kW (over 15 minutes) to supply hot water

point is longer. It is difficult to say how long exactly, as it is possible that the setting was raised during the day, but the temperature rises from the dawn minimum of 17-18°C to 19-20°C within 3 hours. After that, the temperatures rise very gradually to 20-21°C throughout the day.

The "reactive" (i.e. warm-up) and "resistive" (i.e. steady state) heating loads can be seen in the examples of Figure 14.3. Initial outputs are 7-9 kW during warm-up periods, falling quickly to averages of 2-3 kW for house 35 and 3-4 kW for house 38. During the extremely cold weather on 13th January 1982 (Figure 14.3d), the space heating output in house 38 averages about 5 kW. This is for an internal average temperature of about 20°C and an average outside air temperature of about - 8°C - a differential of 28°C. Given that the total heat loss of the house is about 215 W/°C (Chapter 8), the gross heat requirement would be about 6 kW - the extra 1 kW is probably provided by incidental gains.

The ability of the heating system to provide high comfort conditions over a wide range of weather conditions is illustrated in Figure 14.4. This shows living room, hall and main bedroom temperatures, at 8 p.m. for house 38, correlated against daily average outside air temperature over the 1981/82 heating season. Apart from three days when the occupants were probably absent, temperatures are between approximately 20°C and 22°C for the living room and hall, and between 17°C and 21°C for the bedroom, even for daily average outside air temperatures down to -12°C.

It is possible that slightly smaller radiators could still have heated the house adequately. This is illustrated in Figure 14.5. Here, the peak space heating demand measured over one hour has been identified for each day of the heating season. The number of days (as a percentage of the total) for which the peak demands is above a given value (shown on the horizontal axis) is then plotted against the value itself. For example: for 100% of the days the peak hourly demand is above 0 kW and for 80% of the days the peak demand is above about 3.5 kW.

This is a cumulative distribution, which tails off at 7.6 kW, about equal to the sum of the radiator outputs. The total radiator output is sufficient to meet the peak demand for 100% of the days. If the output were reduced by 17% to 6 kW, about 10% of the days' peak hourly demand would not be met. In practice, the house would simply take slightly longer to heat up as a result. It is a matter of personal judgement for the heating system designer, however, as to whether this constitutes a worthwhile financial saving or whether the extra capacity is justified on comfort grounds.

### 14.3.2 Domestic hot water and boiler size

Figure 14.6 shows how the boiler operates in short, sharp bursts of up to 9 kW in supplying domestic hot water. These very high outputs, if concurrent with high space heating demand, bring the total boiler output to 15-16 kW, close to its maximum rated output.

This is seen in Figure 14.7, which shows frequency distributions (percentage of operation time) of boiler output for hot water and space heating purposes separately, and for the total output (house 38). The analysis is based on 15 minute summations.

Space heating outputs, according to the heat meter measurements, extend up to 12-13 kW. This corresponds to early morning warm-up periods, when outputs are higher than the 7.2 kW rated output of the radiators, due to the thermal inertia of the system and the addition of pipe losses (~1 kW).

Hot water outputs range up to 9 kW. These occurrences correspond to periods of heavy hot water use (not necessarily concurrent with peak space heating). As the boiler can deliver 17.6 kW, the maximum rate of heat input to the cylinder is limited only by its heat exchanger efficiency. For an input of 9 kW, to raise 30 gallons of water from 20°C to 60°C would take about 45 minutes, which corresponds to the manufacturer's claims for minimum recovery time. This gives comforting creedence to the measurements.

Even if the space heating output were 9 kW, there would still be 8.6 kW of boiler capacity remaining for hot water use, which the cylinder is capable of absorbing.

Clearly the boiler is oversized. Figure 14.4c shows the total boiler output extending to 16 kW, while only operating 14% of the time above 8 kW. Furthermore, it only operates at the higher outputs by virtue of the fact that the cylinder is able to absorb the 8 or 9 kW capacity that is available even when the space heating output is at its maximum. If the boiler size were only 10 kW, there would still be the normally accepted minimum of 3 kW for hot water for periods when the space heating output was running at its maximum of about 7 kW. As previously discussed, the radiator outputs could probably be reduced by 17% to 6 kW, requiring a boiler of 6 + 3 = 9 kW. This is about half the existing boiler size.

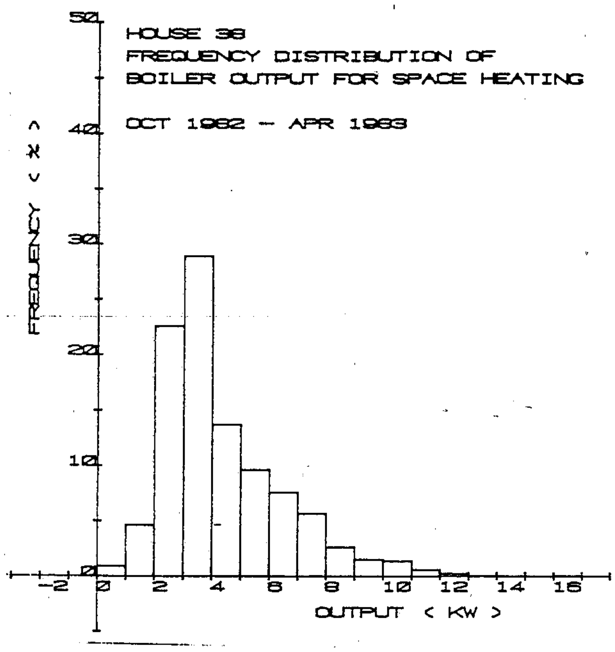
The reader is reminded that this discussion is based on house 38 which has the highest internal temperatures (Oct-Apr while-house average ≈20°C) and a hot water consumption typical of a 4 person family (~3300 kWh/yr).

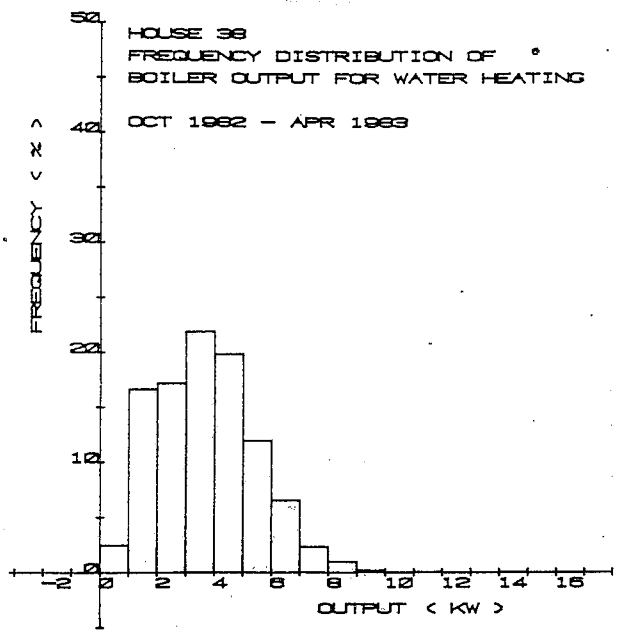
### 14.3.3 Intermittent heating

The examples shown so far in this chapter are for houses with single heating periods of 15-18 hours. For an intermittently heated house, it might be expected that boiler outputs are generally higher, as there are more occurrences of warm-up conditions.

Figure 14.8 compares total boiler output for three continuously heated houses and one intermittently heated house (house 36). In this house the general heating pattern was two periods per day, morning and evening, totalling 6-8 hours, with continuous heating on some weekends and during particularly cold weather.

As a result, the "tail" of the distribution (Figure 14.8d) is larger, reaching maximum outputs of over 17 kW. However, the difference is not great, and a reduction in boiler size is likely to be equally as appropriate as for the continuously heated houses. Again, the main reason for the boiler output extending to its maximum is because the hot water cylinder is able to absorb the excess boiler capacity of up to 9 kW that remains even under conditions of peak space heating demand.



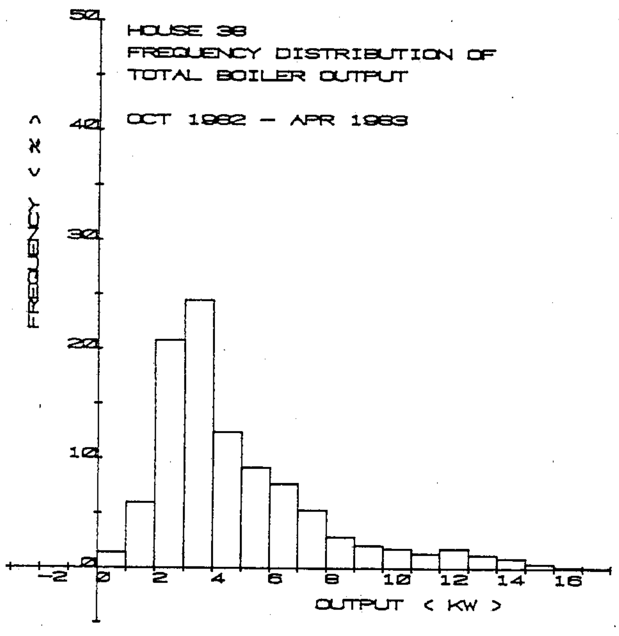
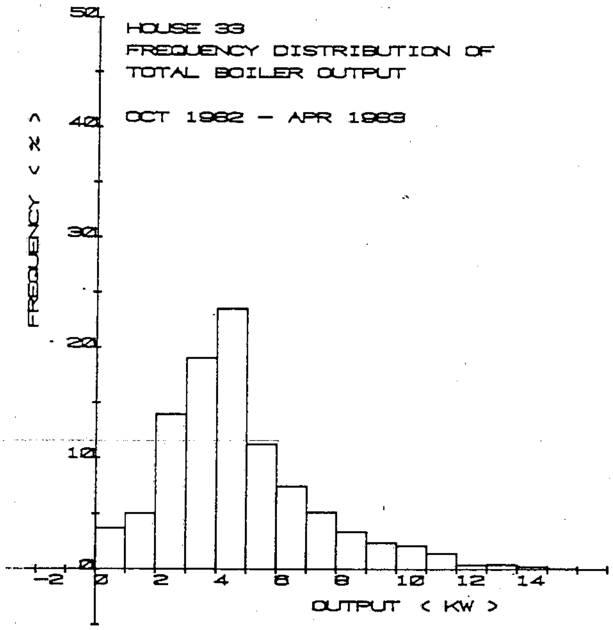
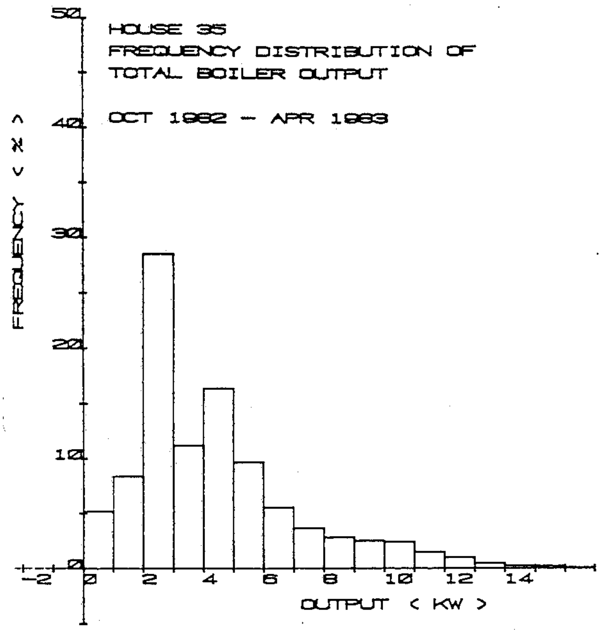



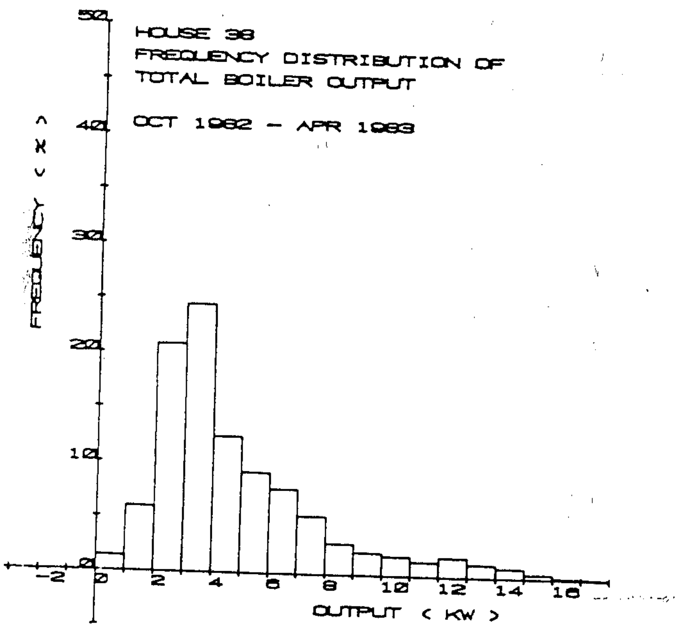

Figure 14.7 Frequency distributions of boiler output for space heating, hot water and total (15 minute summations)



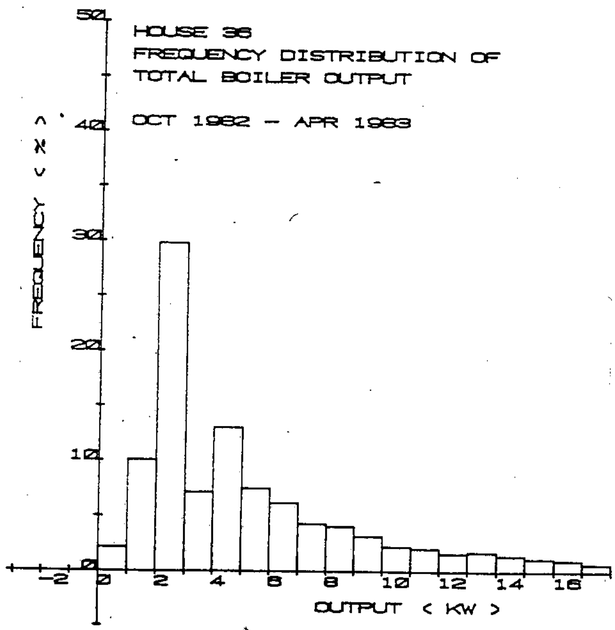

a. Continuous




b. Continuous




c. Continuous




d. Intermittent

Figure 14.8 Boiler outputs for continuously heated houses (a-c) and intermittently heated house (d).

### 14.3.4 Upstairs heating

Separate measurements of downstairs and upstairs space heating consumptions were made in one house (house 33) over the 1982/3 heating season, using two heat meters. The monthly values for each are given below:

| Month | Downstairs heating kWh | Upstairs heating kWh | Total kWh |
|---|---|---|---|
| Sept. 82 | 16 | 0 | 16 |
| Oct. | 355 | 32 | 387 |
| Nov. | 626 | 59 | 685 |
| Dec. | 952 | 158 | 1110 |
| Jan. 83 | 813 | 73 | 886 |
| Feb. | 906 | 170 | 1076 |
| Mar. | 618 | 91 | 709 |
| Apr. | 466 | 54 | 520 |
| May | 206 | 0 | 206 |
| TOTAL | 4958 | 637 | 5595 |

Upstairs heating accounted for only 637 kWh out of 5595 kWh, or 11% of the total.

Analysis of temperatures elsewhere in this report show that bedroom temperatures were comparatively close to downstairs in this house. Since only 11% of the total heat consumption was required upstairs to maintain relatively high bedroom temperatures, it is tempting to pose the question of whether upstairs radiators are required at all in houses as well insulated as these.

However, it has already been seen that low temperatures can occur in unheated bedrooms (probably with the doors closed), when the downstairs is only heated to about 18°C (see house 35 in Chapter 13).

Furthermore, housebuyers spending £40,000 on a 4-bedroom detached house are likely to expect the option of heating all rooms to the temperature of their choice. It is unlikely, therefore, that developers would install downstairs-only heating systems in houses of this type.

Lastly, the occupants of house 33 were asked whether they would be happy to have no upstairs heating, and the answer was a definite "no".

Given that upstairs heating in houses of this type is to be installed, it is particularly important to provide thermostatic radiator valves to avoid heating upstairs rooms more than is required by the occupants. This is discussed in detail later.

## 14.4 Boiler efficiency

### 14.4.1 Heat output vs. gas input

One way of representing the efficiency of a gas boiler is to plot heat output against gas input. This is shown for house 33, on a daily basis, in Figure 14.9.

Although it is an over-simplification to say so, the slope of the best straight line fit to the data can be regarded as an estimate of the maximum or asymptotic efficiency of the boiler, i.e. the efficiency at full load, and the x-axis intercept is an estimate of the boiler standing losses, mostly the pilot flame.

### 14.4.2 Part-load boiler efficiency characteristics

The data can be re-plotted in the form shown in Figure 14.10. Boiler efficiency is plotted against the part-load fraction where:

$$\text{boiler efficiency} = \frac{\text{heat output over a given period}}{\text{heat input over the same period}}$$

$$\text{part-load fraction} = \frac{\text{heat output over a given period}}{\text{maximum possible boiler output over the same period}}$$

The data is plotted on a daily and weekly basis, from a data sample extending over a full 12 month period.

The part-load characteristic is seen quite clearly, with a drop-off in efficiency occurring at about 20% of full output, when short boiler cycle times reduce efficiencies. The estimated maximum or bench effiency is shown by the dotted line.

This is typical of a low thermal capacity gas boiler - a high efficiency maintained down to low part-loads. The efficiency of a conventional cast-iron boiler would begin to drop off at much higher part-loads than this.

The manufacturers quote a bench efficiency of 75%. The estimate shown is nearer 80%. However, calibration of the heat meters subsequent to the measurements showed that they were over-reading by 3-5%. Allowance for this would bring the estimate in line with that of the manufacturers. A value of 75% has therefore been assumed in Chapter 6, when estimates are made for boiler savings due to the use of this type of boiler.

Although no practical boiler would actually be operating at loads approaching 100% over daily or weekly periods, it is quite clear that the boiler is oversized, with maximum daily loads only about 17% of full load. For most days during the heating season, the fraction is 8-12%. As a result, the boiler is operating well inside the drop-off region, and efficiencies are lower than if either a smaller boiler was used, or the boiler was loaded more heavily.

British Gas have monitored the in-situ efficiency of two commercial boilers; their data is reproduced in Figure 14.11, together with the Linford data.

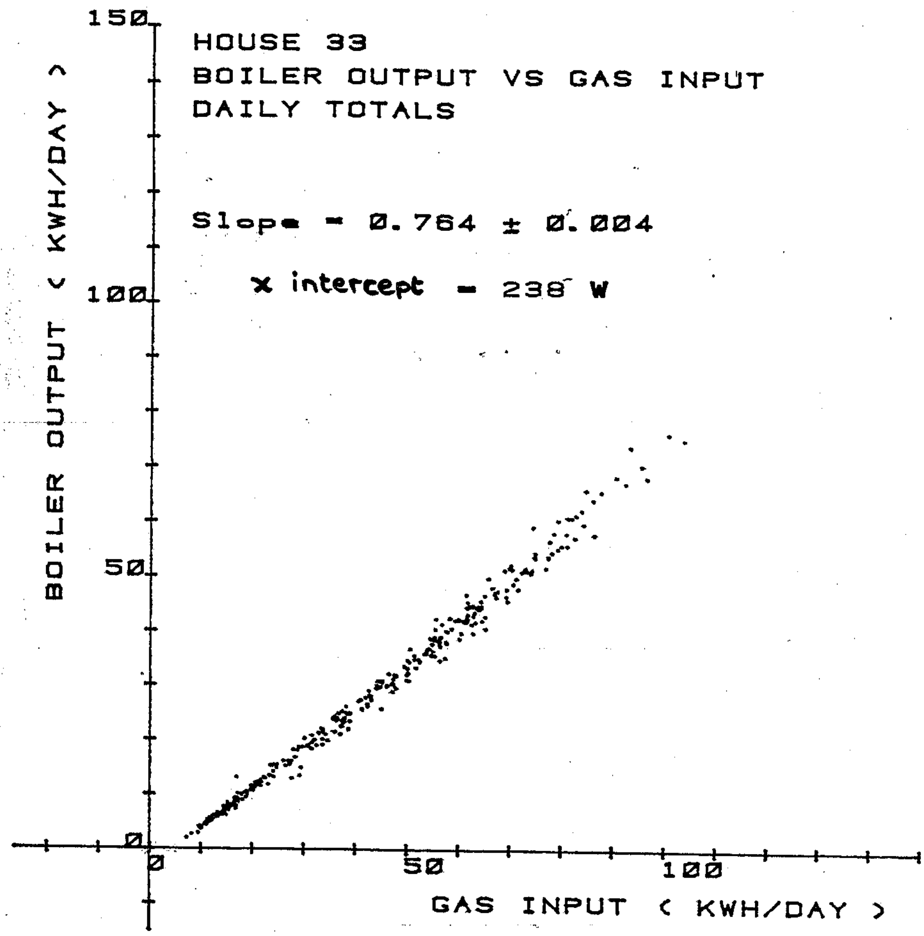



Figure 14.9 Daily heat output vs daily gas input

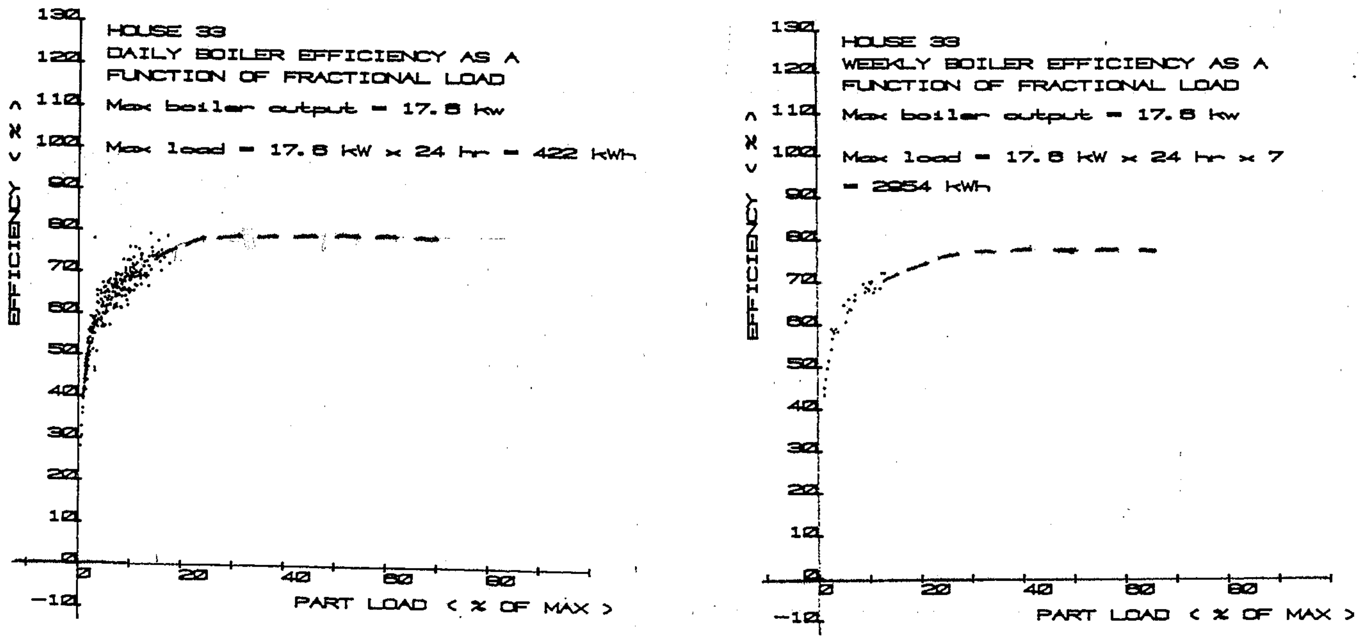



Figure 14.10 Boiler efficiency characteristics under part-load conditions

Weekly average efficiency is plotted against weekly gas input.

All three are similar, except that the Chaffoteaux appears to have a slightly higher efficiency at the higher loads, although this may be false, due to the over-reading of the heat meters by 3-5%. Note however, that the maximum weekly gas input for the Chaffoteaux at Linford is considerably less than that for the other two, which were installed in houses with a design heat loss of 11 kW - over twice that of Linford.

### 14.4.3 Seasonal boiler efficiencies

Figure 14.11 shows the part-load efficiency characteristics. It says nothing of the relative frequency of operation in the different regions of the curve. This is shown in Figure 14.12 in the form of a load-weighted frequency distribution of daily boiler efficiencies. Put more simply, this shows the percentage of the total gas burned in the efficiency bands shown, i.e. nearly 60% of the total gas consumption over the year was burned at between 60% and 70% efficiency etc. The lower efficiencies (40%-60%) correspond to summer hot water use, and only about 16% of the total gas used was burned at these efficiencies.

Monthly and seasonal figures are given in Table 14.2. These show that the annual efficiency was 64.8%, and the winter and summer efficiencies 67.1% and 54.8% respectively (winter = Oct-Apr, Summer = May-Sept).

Similar results were observed for two other houses (houses 35 and 38) which were also heated continuously (15-18 hours). However, efficiencies were slightly higher for house 36 which was intermittently heated. Comparing houses 33 and 36:

| | Winter $\eta$ | Summer $\eta$ | Annual $\eta$ | Gas consumed kWh |
|---|---|---|---|---|
| House 33 | 67.1 | 54.8 | 64.8 | 15379 |
| House 36 | 72.4 | 47.6 | 68.5 | 11404 |

The winter efficiency is higher in house 36 than house 33 and the summer efficiency lower. The winter efficiency is higher because house 36 was usually intermittently heated while house 33 was continuously heated throughout the day and evening. The boiler in house 36 was therefore working at the higher end of its efficiency curve more often than house 33.

The summer efficiencies are lower for house 36 due to a lower hot water use (two-thirds that of house 33).

## 14.5 Performance of controls

### 14.5.1 Interaction with solar gains

The two space heating thermostats are situated in the living room and main bedroom. Both these rooms are on the south side of the house, so that the heating system will be responsive to solar gains.

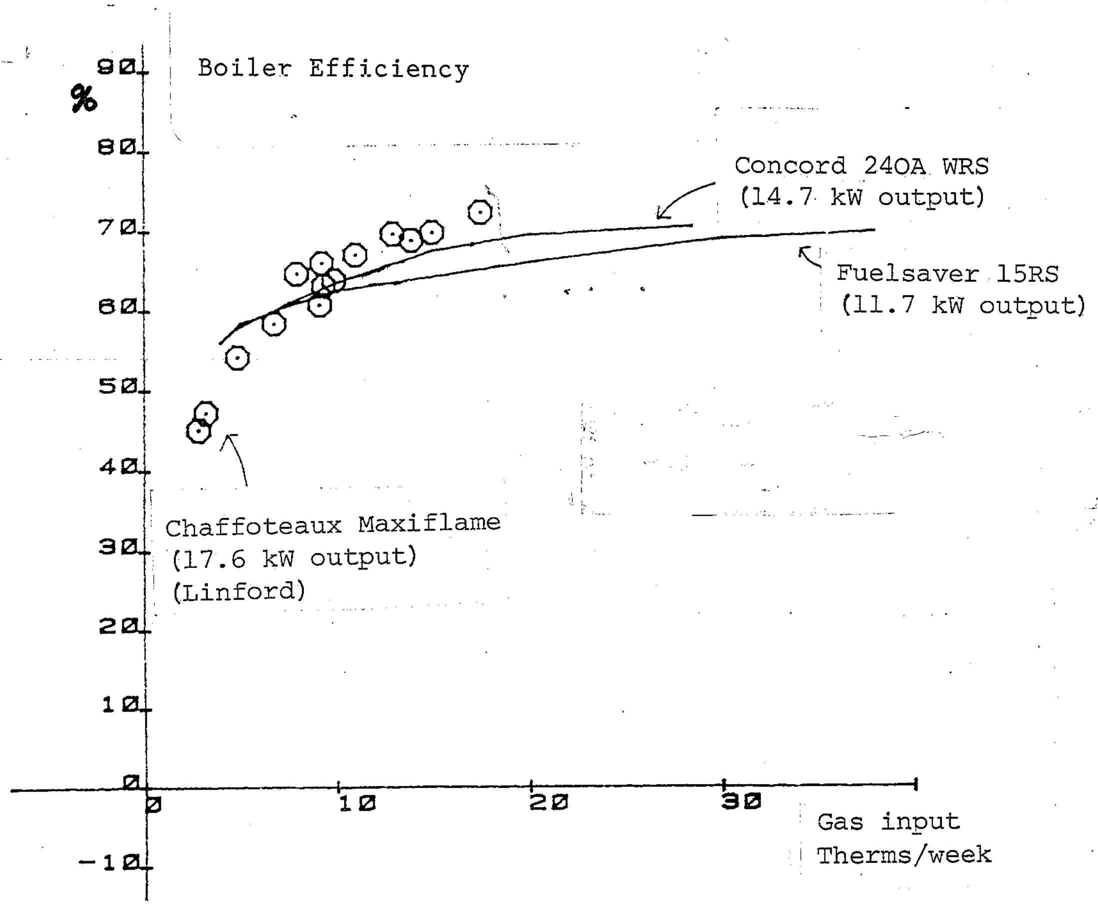



Figure 14.11 Efficiency of three low thermal capacity gas boilers

Concord and Fuelsaver curves from 'Gas Marketing', July 1983, p.22-24.

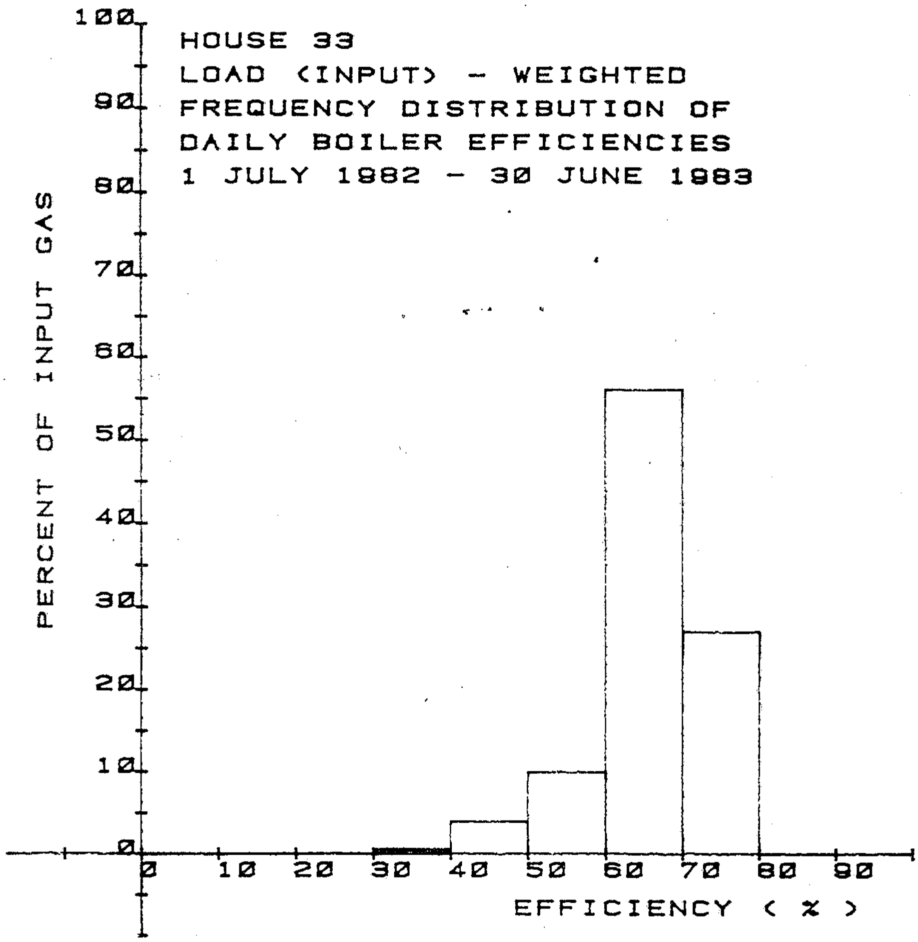



Figure 14.12 Proportions of gas burned at different efficiencies - e.g. nearly 60% of total gas consumption was burned at 60-70% efficiency. Only 16% of gas was burned at below 60% efficiency.

Table 14.2 Monthly and seasonal boiler efficiencies House 33

| MONTH | GAS IN KWH | HEAT OUT KWH | BOILER EFFICIENCY % |
|---|---|---|---|
| Jul 82 | 390 | 185 | 45.9 |
| Aug | 403 | 185 | 45.9 |
| Sep | 510 | 255 | 50.0 |
| Oct | 1054 | 673 | 62.9 |
| Nov | 1489 | 969 | 65.1 |
| Dec | 2130 | 1471 | 69.1 |
| Jan 83 | 1899 | 1286 | 68.0 |
| Feb | 2094 | 1464 | 69.9 |
| Mar | 1768 | 1153 | 65.2 |
| Apr | 1450 | 966 | 66.6 |
| May | 938 | 589 | 62.7 |
| Jun | 605 | 346 | 57.1 |
| TOTAL (Oct - Apr) | 11884 | 7978 | 67.1 |
| TOTAL (Sep - May) | 2846 | 1560 | 54.8 |
| ANNUAL TOTAL | 14730 | 9538 | 64.8 |

This arrangement has been successful, as can be seen in Figure 14.13 (top), which shows room temperatures, space heating output, outside air temperature and south facing solar radiation for one dull day followed by two sunny days. Outside air temperatures do not vary greatly over the period, and the gaps in the shaded heating curve are due largely to solar gains. On each of the sunny days the heating is turned off completely by about 10 a.m., and does not come on again until 3-4 p.m., despite outside air temperatures below $0^{o}C$.

During the middle of the day, the living room and south bedroom "overheat" slightly. However the temperature in the north bedroom begins to fall as soon as the heating goes off, causing the room to be slightly underheated (compare with the dull day on the 9th January) - the dotted lines indicate the probable temperature trace in the absence of solar gains. This indicates the slight drawback of the control strategy used - north-facing rooms can be underheated on sunny days due to solar gains in the south facing rooms turning off the heating system completely.

However, the other example of 21-22 February 1983 in Figure 14.13 shows the opposite effect - the temperature in the north bedroom rises more rapidly and to a higher level on the sunny day than the dull day, due in part to the transfer of some solar gains from the south (the outside air temperature is also rising). The temperature rise is not as marked as in the south rooms, as would be expected.

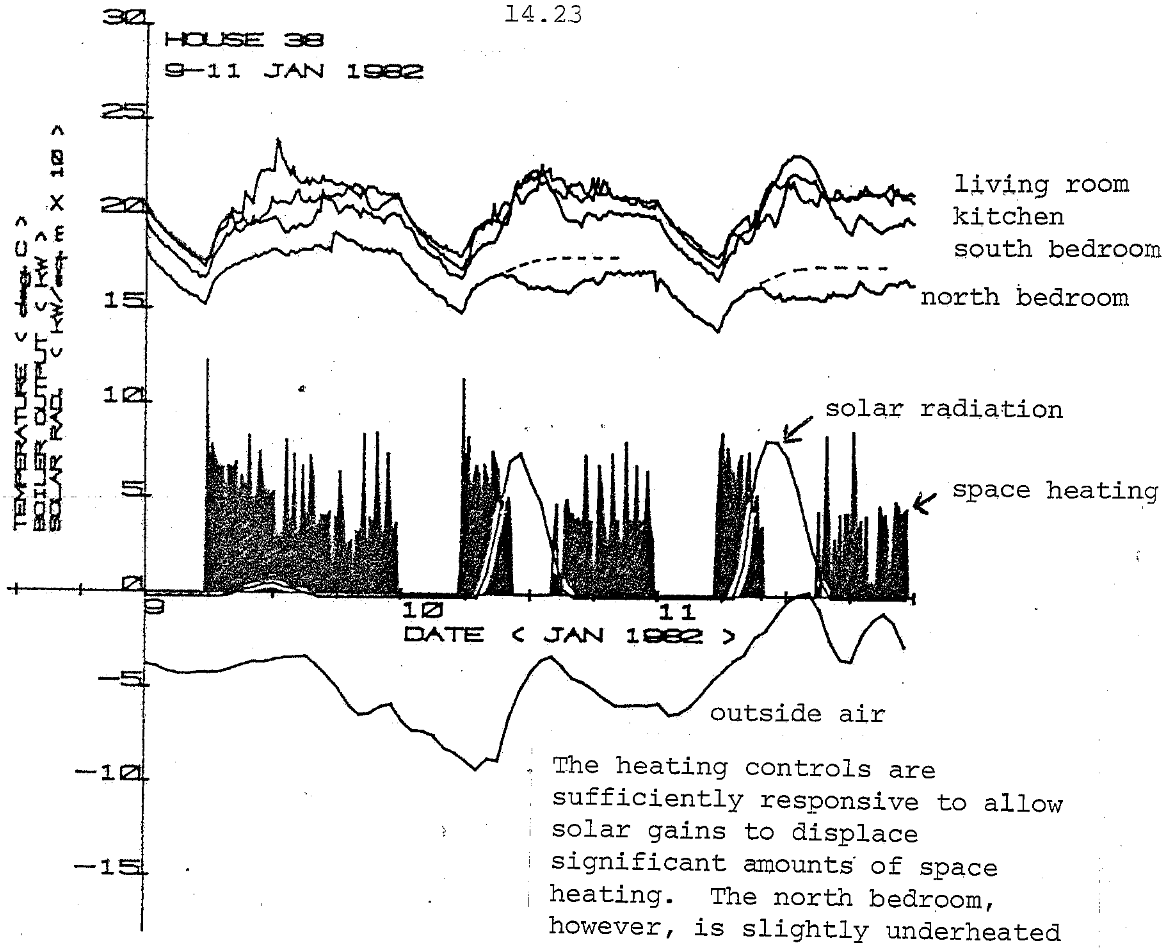
The difference between the two examples may simply be that the interconnecting doors (via the landing) were open in the February example but closed in the January example.

The occurrence of underheating is relatively rare in the data, and the effect is small ($1-2^{o}C$), as it is alleviated by the thermal mass.

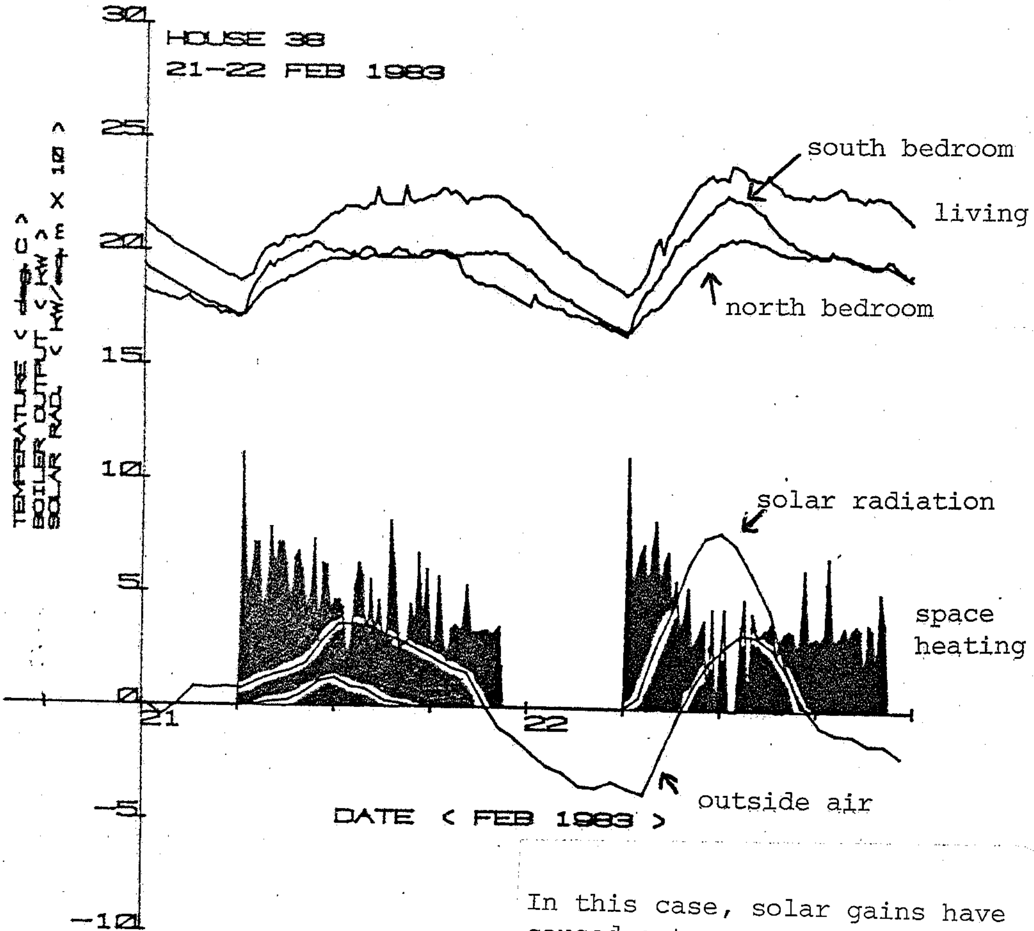
14.5.2 Thermostatic radiator valves

Radiators in rooms other than the living room and main bedroom are fitted with thermostatic radiator valves, to provide flexible downward temperature control in partly-used rooms. These have worked successfully and the occupants were pleased with their effectiveness and ease of use.

An example of its use for a north-facing bedroom is shown in Figure 14.14. The control temperature is about $2^{o}C$ lower than that of the living room thermostat. In each case the control "bandwidth" - fluctuations around the set point - are very small (the data is 15 minute samples) due to the thermal mass.




The heating controls are sufficiently responsive to allow solar gains to displace significant amounts of space heating. The north bedroom, however, is slightly underheated as a result.




In this case, solar gains have caused a temperature rise in the north bedroom as well as the south facing living room and bedroom

Figure 14.13

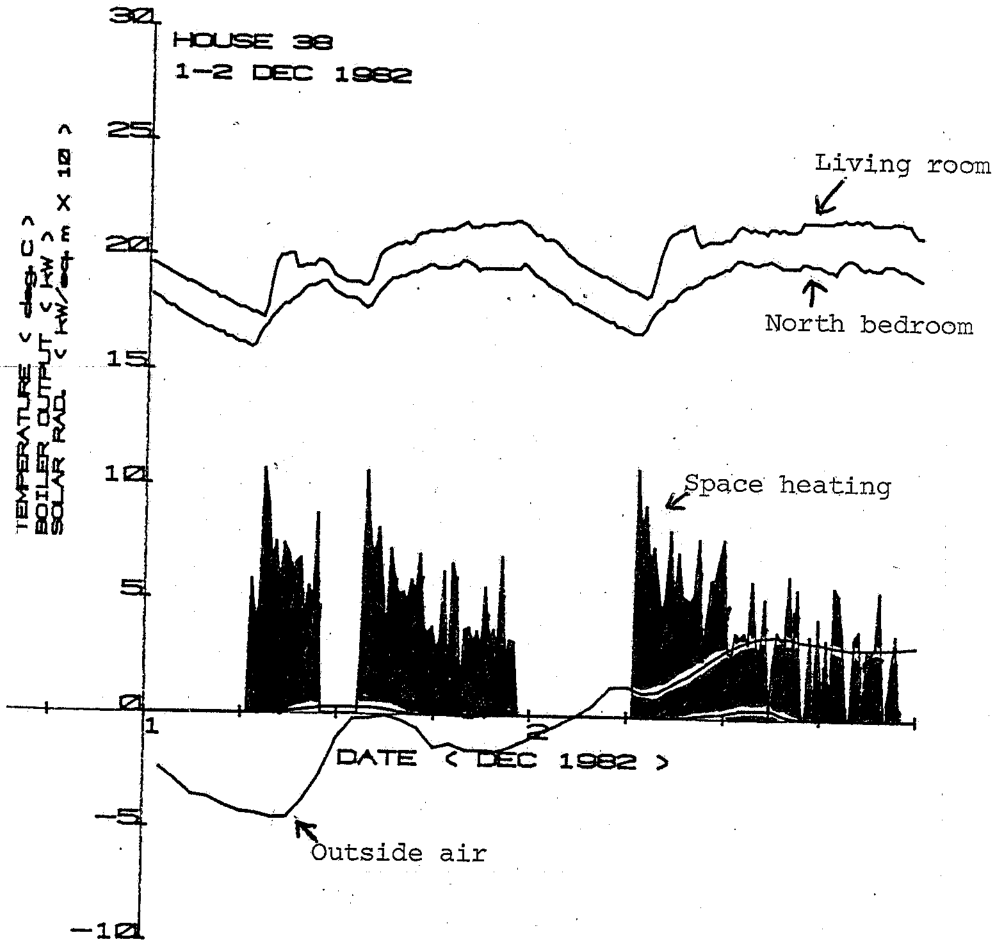



Figure 14.14 The thermostatic radiator valve in the north bedroom controls the room temperature at a lower level than the living room, which operates on a wall thermostat. The control "bandwidth" is very small in each case due to the thermal mass of the house

# 15. CONCLUSIONS FROM PERFORMANCE RESULTS

CONTENTS



At the end of each chapter in section V conclusions are listed. This chapter simply brings together those conclusions for convenience to the reader.

# 15. CONCLUSIONS FROM PERFORMANCE RESULTS

## 15.1. Fabric Heat Losses

The use of regression analysis to establish the overall specific heat loss and the measurements of temperature and heat flux for different elements shed light on the characteristics of the fabric heat losses, resulting in the following conclusions:-

1. With the exception of the floor, the performance of the fabric elements has been much as expected. The heat loss through the walls, roof and windows has been within 25% of the theoretical predictions.

2. It was estimated that cold bridges accounted for 5% of the total fabric heat loss of 215 W/°C.

3. The heat loss through floor, however, was almost twice as high as theory would suggest. The measured U-value being approximately 0.9 W/m² °C, considerably larger than the figure of 0.5 W/m² °C predicted.

4. It has become clear that the actual understanding of the mechanisms of solid floor heat loss is extremely poor. The body of knowledge in the U.K. rests almost entirely on calculations made 30 or more years ago. These calculations did not include the dynamic properties of floor loss. There appears to have been no systematic programme of measurement of solid floor heat loss in the U.K.

   Although the calculation methods available make it clear that soil conductivity is an important factor in solid floor heat loss, this is not made clear in the data available to architects in the CIBS Guides.

5. The addition of 50 mm of extra insulation over the floor reduced the heat loss by approximately 25%, though a higher figure would be possible if the insulation had extended under the partition walls.

6. The heat loss of this floor structure would appear to be best expressed in relation to a near constant deep ground temperature of about 10-12°C.

7. It would seem desirable that there is a proper programme of investigation of solid floor heat loss, especially at insulation levels compatible with the current Building Regulations.

## 15.2. Infiltration and Ventilation

Analysis of measurements of air leakage and infiltration rates and the development of empirical equations to predict infiltration and ventilation rates resulted in the following conclusions:-

1. The houses were much more airtight than was expected.

2. Pressurisation tests showed that leakage areas were considerably smaller than "normal" U.K. houses.

3. Measured infiltration rates in the test house varied between 0.2 and 1.2 ac/h, and were typically 0.4-0.5 ac/h. This house was the least well-sealed of five that were pressure-tested.

4. The monitoring in the test house enabled a theoretical model to be developed for the prediction of infiltration and ventilation rates in the test house, which could be extended for the occupied houses.

5. Window opening during the mid-winter months was very low. Only in one house did the level of window opening during spring and autumn lead to substantial increases in air change rates above background infiltration rates.

6. Average air change rates (infiltration + ventilation) in the occupied houses during the space heating season are estimated to be between 0.3 and 0.4 ac/h.

7. Heat losses due to infiltration and ventilation were estimated as below 20% of the total energy consumption.

8. While the construction was generally tight, problems were experienced with the french windows which had to be extensively draughtstripped, and in some cases re-hung. The windows were well-sealed.

9. The effect of sheltering was found to be important. Sheltering from the strong prevailing S.W. winds was estimated to be worth about 450 kWh/yr.

## 15.3. Solar Gains

A major objective of the project was to assess the impact of solar gains on the use of energy in these passive solar houses. The following conclusions arose from this investigation:-

1. The Linford houses have worked well as direct gain passive solar houses.

2. The experiment allowed the solar gains to be expressed as being equivalent to a clear south-facing solar aperture. This solar aperture is less than the total southerly glazing area of 16 m² and takes into account the transmission through the glazing and the absorption and re-reflection at the internal surfaces.

3. The test house measurements give an equivalent solar aperture of 10 m² ± 1 m² for unobstructed windows and 8 m² ± 1 m² for full net curtains.

4. Measurements in the occupied houses reinforce these estimates of solar aperture, with values of between 6.8 and 10.7 $m^2$.

5. For a solar aperture of 10 $m^2$ the absolute solar contribution would be 2500-4500 kWh/yr, depending on the assumed length of the heating season. This figure compares well with similar estimates obtained from simple energy balances in four occupied houses. The average solar contribution in the four houses was 3573 kWh/yr which is equivalent to 24% of the gross heating requirement or about two-thirds of the net space heating consumption of 5748 kWh/yr.

6. Estimates have been made of the marginal solar energy saving which results from the passive solar measures. This has been done by comparing computer models of the houses and 'normal' randomly orientated, overshaded, dual aspect houses with net curtains. A typical Linford house has the potential to save around 1400 kWh/yr of useful space heating energy over the normal house. The solar savings are dependent on internal temperature and incidental gains and could be larger if higher temperatures are assumed thereby extending the heating season.

7. Of the 1400 kWh/yr, about a third is due to correct orientation and avoiding overshading, one third is due to concentrating the glazing on the south side and the remaining third is due to avoiding net curtains and window clutter.

8. The solar apertures were less than the expected value of 13 $m^2$ for clear unobstructed glazing which was used in initial computer modelling. This could be due to the following reasons.

   (a) Over optimistic values for the absorptivity of rooms in the model.

   (b) Overshading by the roof eaves and window reveals.

   (c) Over estimates of the usefulness of solar gains upstairs.

   (d) A problem of definition of external air temperature under conditions of high solar fluxes.

9. The concrete ground floor slab cannot be considered as 'primary thermal mass'. In practice carpets isolate the floor slab from solar gains with as little as 15% of incident radiation on the floor being transferred to the storage.

10. It was found that insulating the floor slab did not decrease the apparent solar aperture.

## 15.4. Incidental Gains

The measurements of electrical energy consumption, energy for hot water and cooking, together with estimates of occupancy patterns have led to good estimates of incidental gains. Conclusions drawn from this work are as follows:-

1. Incidental gains contribute between 4000 kWh and 7800 kWh per year to the gross heating requirement.

2. The incidental gains typically constitute 38% of the gross heating requirements and are of the same order as the useful space heating consumption.

3. The average daily gains during the heating season varied between 15.7 and 29.5 kWh/day with a mean of 21.7 kWh/day.

4. These gains are made up from:

| | |
|---|---|
| occupants | 17% |
| appliances | 40% |
| cooking | 12% |
| hot water | 19% |
| boiler casing losses | 12% |

## 15.5 Energy Balances

Calculations of the total house heat loss, incidental gains, useful space heating consumption and solar gains allowed an estimate to be made of the energy balances of the occupied houses, with the following conclusions.

1. Solar gains constituted between 17% and 33% of the gross heating requirement.

2. Incidental gains were 32%-43%.

3. Useful space heating contributed 32%-42%.

4. The average breakdown for four houses over a heating season was

| | | |
|---|---|---|
| solar gains | 3573 kWh | 24% |
| incidental gains | 5771 kWh | 38% |
| space heating | 5748 kWh | 38% |

The heat inputs are balanced by heat losses through the fabric elements and via ventilation. These are as follows:

| | | |
|---|---|---|
| Roof | 1056 kWh | 7% |
| Walls | 3018 kWh | 20% |
| Windows | 4679 kWh | 32% |
| Floors | 3471 kWh | 23% |
| Doors | 453 kWh | 3% |
| Ventilation | 2415 kWh | 15% |

## 15.6. Comfort Conditions

In these well-insulated houses air temperatures give a good approximation to comfort conditions. Extensive analysis of these internal temperatures led to the following conclusions:-

1. There was a wide range of temperatures recorded. Whole house winter <u>averages</u> ranged from 16.3°C to 20.1°C, and the average of 6 occupied houses was 18.9°C.

2. These are among the highest temperatures recorded in surveys of U.K. housing.

3. The temperatures were a function of occupant choice and thermostat setting. The heating system was sufficiently oversized to be able to provide more or less any desired temperature, even at external temperature well below zero.

4. It is fair to assume that the energy conservation measures have resulted in such low fuel bills that occupants are not constrained in the choice of temperature.

5. Thermal mass produced very stable internal conditions. Typically cooling overnight was restricted to only 2 or 3°C.

6. Summer overheating was not found to be a problem.

## 15.7. Heating Systems and Controls

Measurements of the gas input to the boiler, the heat output to the heating system and the resulting room temperature have revealed some interesting insights into the functioning of the heating system with these conclusions:-

1. Heating system is able to maintain high levels of comfort even in extremely cold weather (down to −17°C).

2. Radiators appear to have been sized 40% above steady state heat loss. This has resulted in very satisfactory warm up times of 2-3 hours. It is possible that the output of the radiators could be reduced by 20% without affecting warm-up rates except in the severest of weather.

3. The 17.6 kW boiler is considerably oversized. It is estimated that the boiler could be reduced to 10 kW or less without adversely affecting comfort conditions or the supply of hot water.

4. The oversized boilers were working typically at an annual efficiency of 65%. With the use of a smaller boiler this might rise to perhaps 70%.

5. The control system was sufficiently responsive to allow the incidental and solar gains to displace heating from the boiler.

6. Results from one house show that only 11% of the total heat was supplied to the bedrooms. This suggests that conditions would not be detrimentally affected if the system upstairs was omitted. However, whether this would be acceptable to the occupants or prospective house buyers is doubtful.

# 16. MONITORING & EXPERIMENTAL METHOD

CONTENTS



This chapter gives a summary of the range of measurements undertaken in this project, and gives detailed descriptions of the sensors used and the data logging system. The construction and subsequent use of the database is also described.

# 16. MONITORING AND DATA COLLECTION SYSTEMS

## 16.1 Introduction

The brief for the Linford project was to monitor a small number of houses in considerable detail in order to build up a detailed picture of the thermal performance and energy flows within a highly insulated, thermally-massive, direct-gain passive solar house, and to examine the effects of occupancy and weather conditions on the thermal performance.

The scheme involved only 8 houses, seven being occupied and one used as a test house in which carefully controlled heating experiments could be carried out without the normal disturbances caused by occupants. Thus thermal calibration could be done as accurately as possible using the test house, while the occupied houses provided data on the thermal performance under real conditions over a range of occupancy patterns. The thermal performance of the physical building itself, and the effects on this performance due to occupancy could thus be separated.

This partnership between test-house and occupied-house measurements was very successful and proved to be the corner-stone of the Linford project.

## 16.2 Choice of measurements

At the beginning of any field trial involving occupied houses, it is always difficult to decide on the range and scope of measurements. This is particularly so for an investigative project such as Linford, whose aims were to a certain extent open-ended.

As the project involved houses under construction, sensors and cabling could be incorporated into the structure as construction proceeded, so that there would be little evidence of their existence when the houses were complete. It was realised that there would be no opportunity to retro-fit more sensors once the houses were completed and occupied.

Thus, the policy adopted was to install a comprehensive set of sensors, with some built in redundancy, knowing that as the project proceeded, some sensors might not be used. This is easily justified when it is considered that the cost of installing even a small number of sensors is high; the marginal cost of installing more sensors is low and becomes lower as the number of sensors increases. One is, in fact, paying the premium on an "insurance policy" in advance.

### 16.2.1 Sensors installed

A set of sensors was installed in every house (including the test house) in order to measure the following parameters:

| | |
|---|---|
| Air temperatures in every room (two in living room) | (14 in all) |
| Loft air temperature | |
| Floor and wall surface temperatures in living room | (4 in all) |
| Floor and wall heat flow in living room, and bedroom ceiling | (5 in all) |
| Total gas consumption | |
| Total electricity consumption | |
| Cooking gas or electricity consumption | |
| Space heating energy consumption | |
| Hot water energy consumption | |
| Programmer status | |
| Window openings | |
| Internal and external door openings | |

The weather station erected in the test-house garden was designed to measure the following:

Air temperature
Global vertical, south-facing radiation intensity
Global Horizontal solar radiation intensity
Diffuse horizontal solar radiation intensity
Wind speed
Wind direction
Humidity

(The three radiation intensities: integrated)

Additional instrumentation in the test house included ventilation rate measuring equipment, and electronic temperature controllers for the heating experiments. A detailed description of the monitoring equipment is given later.

### 16.2.2 Sensors used

Of the parameters listed, some sensors did not work, and of those that did, not all were used simultaneously as to do so would have exceeded the available data-logging capacity. Also, some sensors such as the internal door openings and programmer status were not commissioned due to lack of time and available manpower. Unfortunately, this included important parameters such as space heating and hot water consumption and gas and electricity consumption in three out of the seven occupied houses.

The final set of sensors selected for long-term monitoring in the occupied houses were:

(i) 4 occupied houses

| | |
|---|---|
| 6 air temperatures: | living room |
| | Kitchen |
| | Hall |
| | Bedroom 1 (south) |
| | Bedroom 2 (south) |
| | Bedroom 3 (north) |

space heating consumption
hot water consumption
total gas consumption
total electricity consumption
cooking electricity/gas consumption
window openings

(ii) 2 occupied houses

6 air temperatures (as above)

In one occupied house, it was not possible to record any data other than weekly gas and electricity consumption, due to wiring problems.

(iii) Test house

The long-term set of measurements were:

Air temperatures in all rooms (14 in all)
Loft temperature
Floor and wall heat flux in living room, and bedroom ceiling
Total electricity consumption
Ventilation rate

For the weather station, all sensors installed (listed earlier) were used, although the diffuse radiation measurements did not begin until the second monitoring season.

The list of measurements used in the project are summarised in Table 16.1 showing the areas of analysis where they were valuable. The range of sensors used are listed in Table 16.2, together with manufacturers and approximate cost.

## 16.3 Description of sensors and data-logging system

### 16.3.1 Internal temperatures

Temperatures, both air and surface, were measured with grade II platinum resistance thermometers. These have a resistance of 100 ohms at $0^{o}C$, rising to 138.5 ohms at $100^{o}C$. Their accuracy is about $\pm 0.25^{o}C$. Three-wire lead resistance compensation was used to take account of the long connecting leads (up to 100 metres, or about 5 ohms).

For internal air temperatures, the sensors were mounted inside plastic thermostat boxes manufactured by Satchwell, and fixed to walls, at a height of about 5 ft, away from radiators. The most common position was next to the light switch just inside the door. Figure 16.1 shows a sensor inside the plastic box.

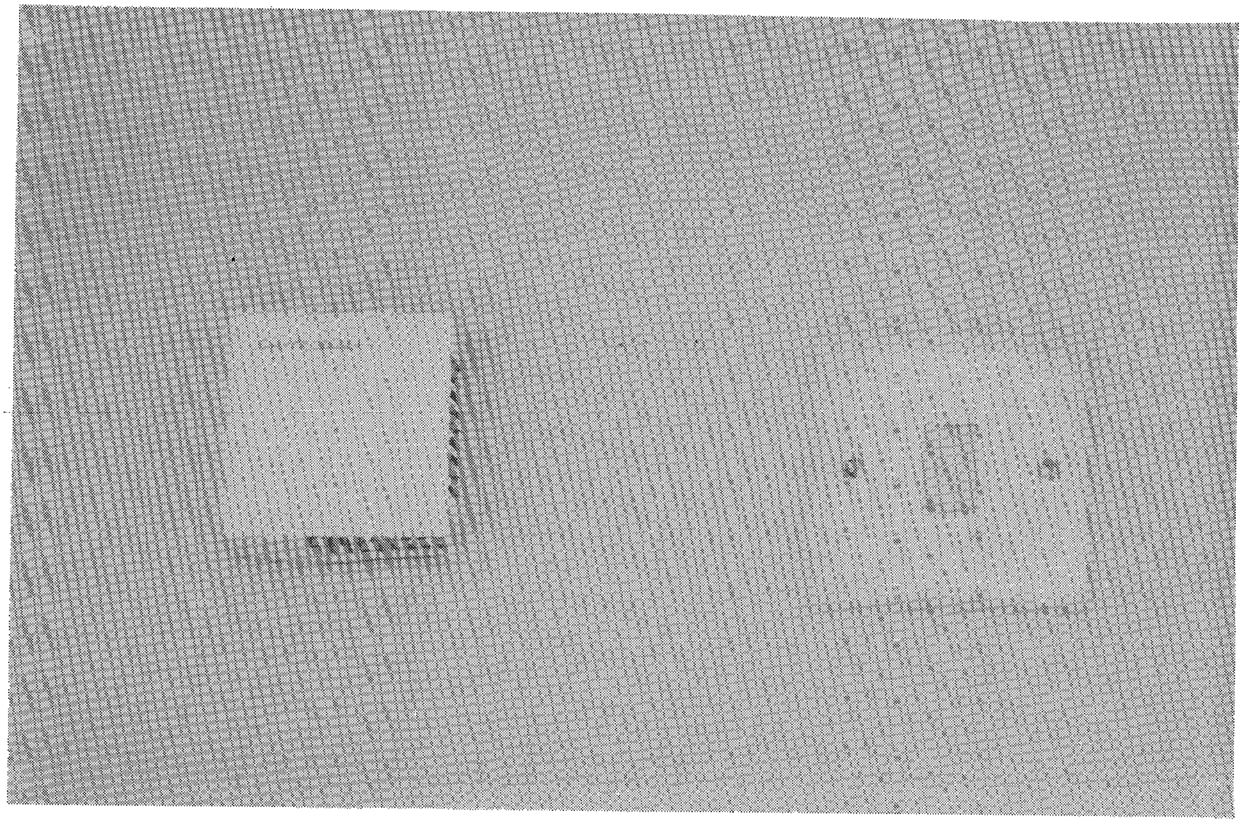
This method of mounting, as any, is a compromise between correctness of measurement and unobtrusiveness. Originally, they were to have been mounted at the end of a 3 inch long plastic stem protruding from a ceiling rose light fitting attached to the wall. This would have given a good measurement of air temperatures, there being plenty of opportunity for air movement around the sensor. However, this was rejected by the developers on the grounds that it would not be acceptable to house buyers, as it resembled a small microphone! This may sound absurd, but it illustrates the need to keep monitoring equipment as unobtrusive as possible when carrying out measurements in occupied houses. The plastic boxes used resembled wall-mounted thermostat boxes, which are a familiar feature in modern houses. They were, therefore, more acceptable to the occupants. As a method of measuring air temperature, it is probably slightly inferior to the plastic stem method of mounting, as it is enclosed in a box (although

Table 16.1 Summary of measurements used in the analysis of Linford data

| | Comfort conditions | Whole house thermal calibration | Heating system + controls | Thermal mass | Estimation of useful solar gains | Energy balance | Summer over-heating | Fuel req. | Boiler efficiency | Inc. gains | Space heating req. | Length of heating season | Use of windows | Ventilation rates | Heat loss through elements | Absorption of solar radiation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Occupied Houses** | | | | | | | | | | | | | | | | |
| Internal temps. | x | x | x | x | x | x | x | | | | | | | x | x | |
| Boiler gas consump. | | x | x | | x | x | | x | x | x | | | | | | |
| Electricity consump. | | x | | | x | x | | x | | x | | | | | | |
| Cooking gas or elec. | | x | | | x | x | | x | | x | | | | | | |
| Space heating | | x | x | x | x | x | | | x | | x | x | | | | |
| Hot water | | x | x | | x | x | | | x | x | | | | | | |
| Window openings. | | x | | | x | x | x | | | | | | x | x | | |
| **Test House (additional)** | | | | | | | | | | | | | | | | |
| Ventilation rate measurement | | x | | | x | x | | | | | | | | x | x | |
| Heat flux | | x | | x | x | x | | | | | | | | | x | x |
| **Weather Station** | | | | | | | | | | | | | | | | |
| External temps. | x | x | | x | x | x | x | | | | | | | x | x | |
| Solar radiation. | x | x | | x | x | x | x | | | | | | | | x | x |
| Wind speed and direction. | | x | | | x | x | | | | | | | | x | | |
| Humidity | | | | | | | | | | | | | | | | |

Table 16.2 Range of sensors used, suppliers and approximate costs

| Measurement | Sensor/device | Supplier | Number | Approximate cost |
|---|---|---|---|---|
| Air and surface Temp. | Platinum Resistance Thermometer | Matthieson Printed Products | 200 | £3 each |
| Structural heat flow | Heat flux meters | OU and TPD | 40 and 2 | £10 and £300 each |
| Fluid heat flow | Heat meters | Kamstrup-Metro | 20 | £110 |
| Gas | Standard domestic 312 cu, ft/hr gas meter (modified) | Southern Gas Board | 16 | £40 including mod. |
| Electricity | Standard domestic elect. meter (modified) | East Midlands Electricity Board | 16 | £50 including mod. |
| Window switches | Micro switches | RS Components | 264 | £0.80 each |
| OU Vent rate rig | Infra red analyser + home made controls + aux equip. | Sieger Ltd. | 1 | £2000 |
| Solar rad. | Thermopile Solarimeter | Kipp and Zonen | 4 | £400 |
| Wind speed | Cup anemometer | Reading Univ. Met. Dept. | 1 | £150 |
| Wind direction | Wind vane | Reading Univ. Met. Dept. | 1 | £150 |
| Humidity | Semiconductor sensor | Vaisala Instruments | 1 | £100 |
| Data collection | Tape cartridge data loggers | Microdata | 6 | £ 5000 each inc. cards |



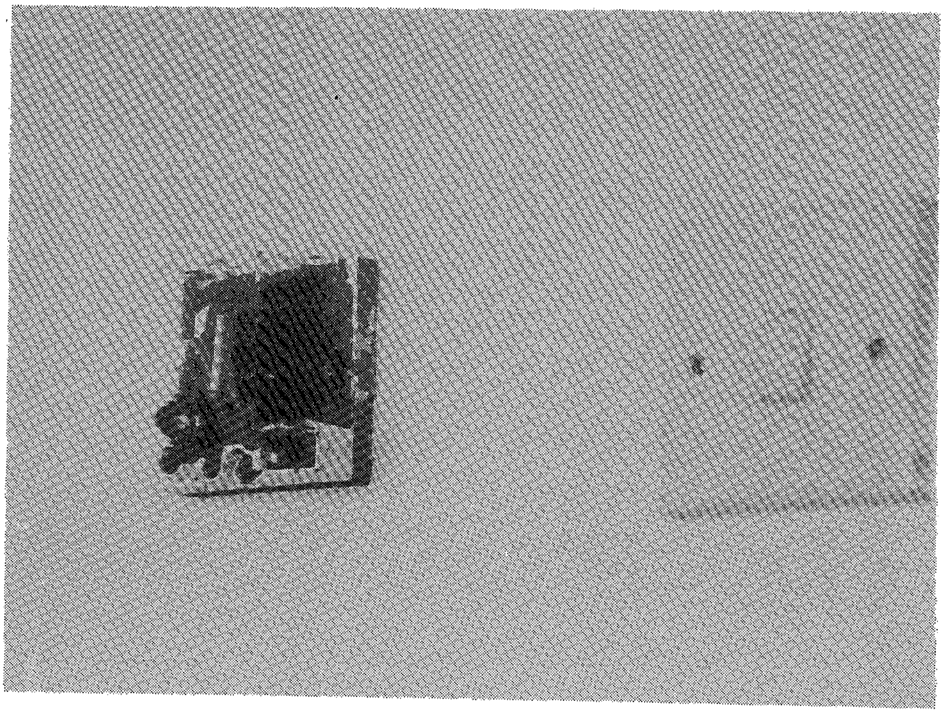


Figure 16.1 Platinum resistance thermometer inside wall-mounted thermostat box measuring air temperature

there were ventilation grills top and bottom) surrounded by plastic material which has some thermal mass. It is also closer to the wall, on the edge of the boundary layer, where the wall surface temperature begins to have an effect on the measured air temperature. However, after some laboratory comparisons of measurements using the two methods of mounting, these disadvantages were considered small enough to be ignored. The boxes had one theoretical advantage over the stem mounting in that the front surface was a polished silver colour, which would offer some protection from solar radiation in the south-facing rooms.

For surface measurements, the sensors were plastered or cemented just below the surface of the walls and floor, next to heat flux meters. Individual sensors were not calibrated, but each signal conditioning card in the data loggers were tested and adjusted to read the correct temperatures, using accurately known standard resistances.

### 16.3.2 Heat flux meters

The principle of heat flux measurement is to measure the temperature difference between the two opposing faces of a thin slab of material with a constant thermal conductivity. The perpendicular heat flow through the slab is then proportional to the temperature difference, as shown in Figure 16.2.

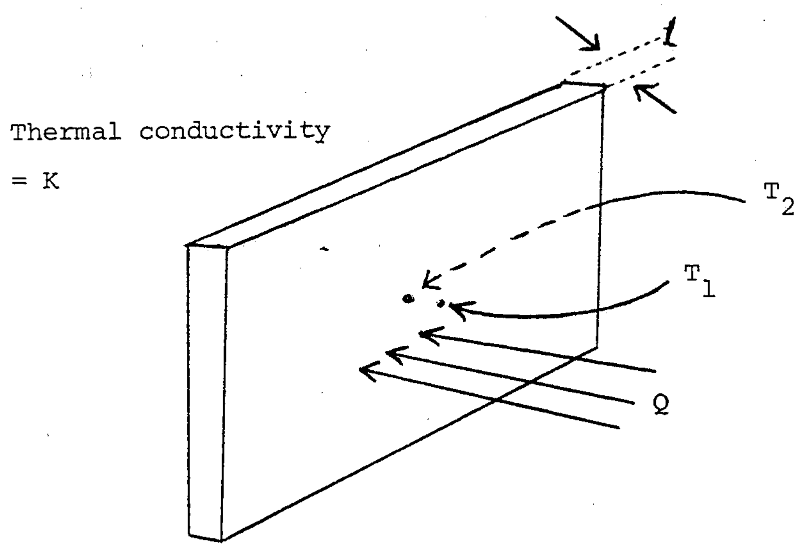



Figure 16.2 Heat flow $Q = \frac{K}{l} (T_1 - T_2)$

The heat flux meters used at Linford were manufactured at the Open University.

#### (i) Construction

Approximately 150 turns of constantan wire are wound in coil fashion around a thin slab of plastic material such as polythene, P.V.C. or perspex (Figure 16.3). The slab is then immersed edge-on in a bath of copper sulphate solution, so that the liquid level reaches half-way up the face of the slab. The constantan coil is then plated with copper to a thickness of approximately 0.025 mm. This is done by connecting the positive side of a d.c power supply to 2 pieces of thin copper plate submerged in the solution, one either side of the slab. The constantan coil was connected to the negative side of the power supply, using a large bulldog clip to ensure electrical contact at the same point of each turn, for as many turns as possible. The constantan coil thus becomes the cathode and the copper plates the anode. The power supply is then adjusted to provide a current of approximately 1 amp, and the coil plated for 4-5 minutes.

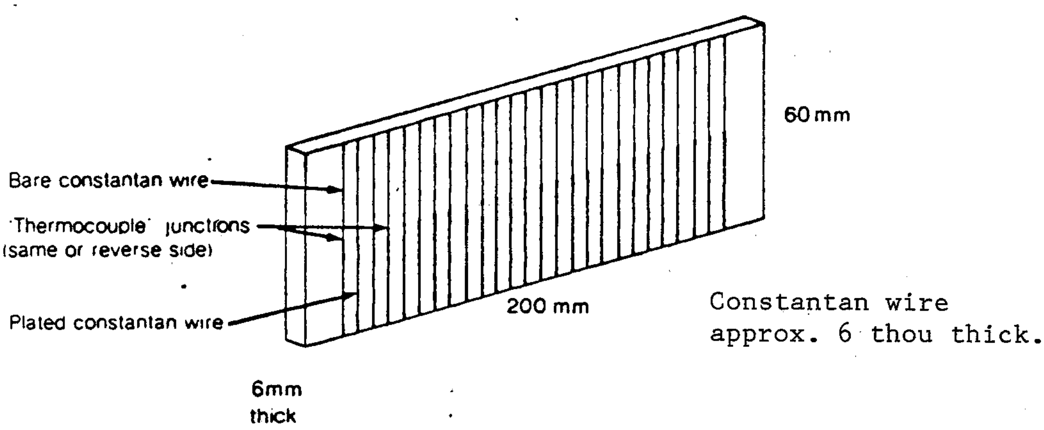



Figure 16.3 Heat flux meter construction.

The half-plated coil resembles a thermopile with as many thermojunctions as there are turns of the coil, successive thermojunctions alternating either side of the polythene slab. A small emf will be generated between successive junctions if a temperature difference exists across the faces of the slab. Each full turn of the coil contains 2 junctions, one either side of the slab. If 150 turns are used, the resulting voltage output from the device is 150 times that of a pair. The entire construction is potted in epoxy resin to protect the delicate wire turnings.

This device was embedded in the walls and floor of the living room, and a bedroom ceiling. For the wall, an area of plaster slightly larger than the heat flux meter itself is stripped off, back to the concrete wall. If necessary, some of the concrete can be chipped away to give sufficient depth to completely cover the heat flux meter.

It was then plastered into the wall, by first smearing a thin layer of plaster onto the concrete surface (soaked with water first), and also on the rear side of the heat flux meter. This was to ensure good thermal contact with the wall. Too small masonry nails were driven through the corners of the heat flux meter to secure it permanently. The heat flux meter was then plastered over and the wall made good.

N.B. It is recommended that for the heat flux meter a plastic material be chosen whose thermal conductivity is as close as possible to that of the material in which it is to be embedded. The higher the total thermal resistance of the wall, the less important this is. However, for thin poorly insulated structures, significant errors may arise due to the distortion of the heat flow in the vicinity of the heat flux meter.

For those used in the walls and floor, polythene was used, with a thermal conductivity of 0.35 W/m $^{o}$C. This compares with about 0.48 for the plaster of the walls and 1.0 for the concrete floor. For the ceilings, PVC was used with a conductivity of 0.16, identical to the quoted value for plasterboard.

(ii) Calibration of heat flux meter

The heat flux meters were calibrated at the Open University, against a commercially available heat flux meter manufactured by Technisch Physische Dienst (TPD) in Delft, Netherlands, costing about £300 each.

The apparatus used for calibration is shown in Figure 16.5. The two types of heat flux meter were slotted into holes cut in sheets of material of similar thermal conductivities to the respective heat flux meters. For the OU device, the polythene slab from which they were made was used; perspex was used for the TPD meters.

The top tray was filled with water at 60$^{o}$C, and the bottom tray filled with ice/water mixture at 0$^{o}$C. This construction establishes a uniform heat flow field around the centre of the apparatus where the heat flux meters are situated. The entire construction was surrounded by 100 mm thick polystyrene insulation to reduce edge effects.

This apparatus enabled calibration of the OU heat flux meters against those from TNO with reasonable accuracy considering the rudimentary nature of its design and construction. The calibration of the TPD meters is quoted to $\pm$5% accuracy. It is estimated that the corresponding accuracy of the OU meters might be $\pm$10%.

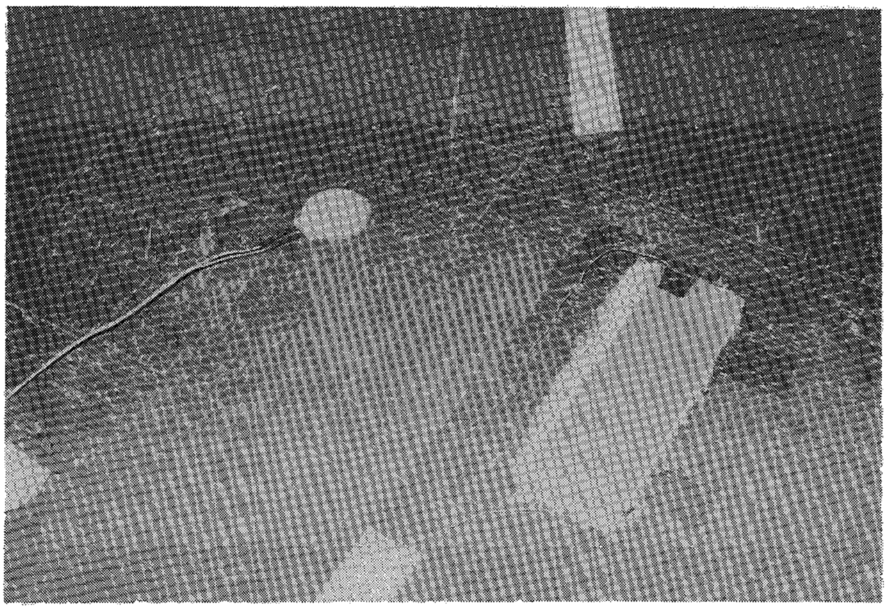


Figure 16.4 Commercial (left) and OU-constructed (right) heat flux meters, surface mounted on a floor for illustration only. Actual measurements were obtained from the OU devices embedded in the walls and floor etc.

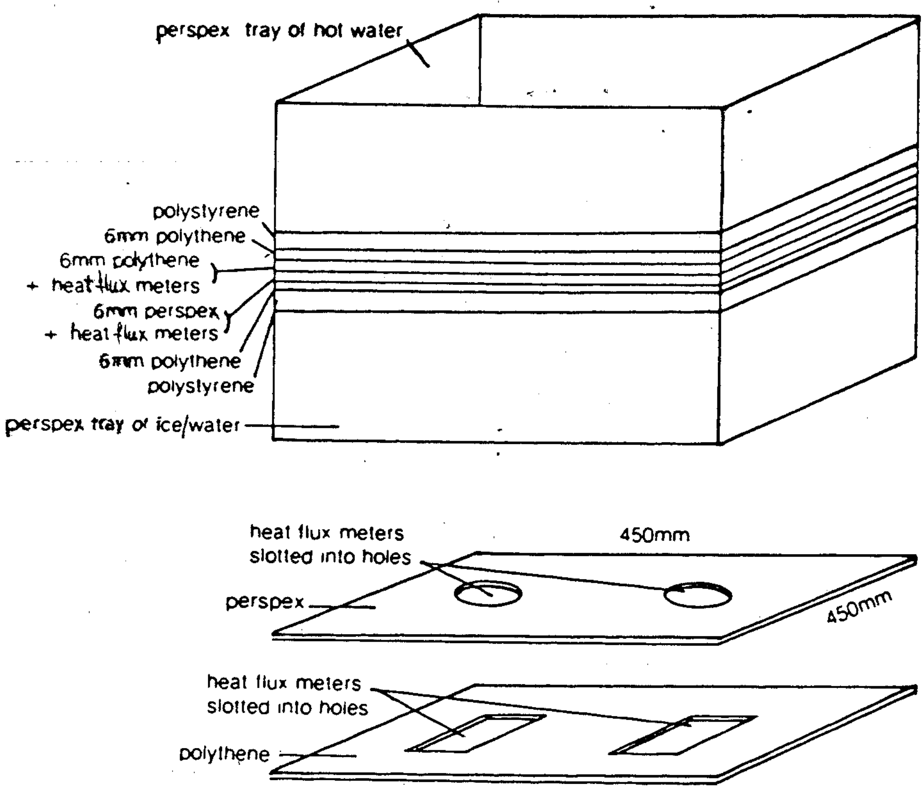



Figure 16.5 Calibration rig used for heat flux meters

The OU meters gave outputs of about 20 W/$m^2$ per mV compared with about 15 W/$m^2$ per mV for the TPD meter.

The output of the OU meters was typically 20 W/$m^2$ per mV, compared with 15 W/$m^2$ per mV for the TPD meters. Outputs in-situ are low. For example, a temperature difference of 15 $^{\circ}$C across a wall of U-value 0.3 W/$m^2$ $^{\circ}$C will give rise to a heat flow of 4.5 W/$m^2$. For this, the heat flow meters give an putput of about 0.23 mV.

Such low outputs need accurate amplification, with attention paid to problems of noise, RF pick-up and input offset drift. Amplifiers with gains of 1000 were used based on ICL 7600 commutating auto-zero amplifier IC's (CAZAMP'S). These amplifier chips cost about £10 each and consist of two amplifiers which continually swop over, one measuring the signal while the other measures and corrects for its own drift. The relatively large area and coil construction of the heat flux sensors makes them very prone to pick up stray mains hum and a suitable filter had to be incorporated in the input of the amplifier.

### 16.3.3 Heat meters

Space heating and domestic hot water consumption were measured directly using Kamstrup-Metro heat meters. This device uses a turbine flow meter to measure the water flow rate, and temperature sensors inserted in the flow and return pipes to measure the temperature difference between flow and return. The two measurements are integrated to give an output in units of energy. Quoted accuracies are ±5% each on flow and temperature difference measurement giving a maximum error of ±10%. Each instrument cost about £120 at 1980 prices. Figures 16.6-16.8 show the components of the instrument and an example of its installation.

The heat meters are battery powered, with resolution of only 10 kWh, the output registering on an electro-mechanical counter. This is sufficient for weekly measurements as at Pennylands, but is far too low a resolution for hourly measurements at Linford. Consequently, they were modified at the OU to give a pulse output for connection to a data logger. The outputs were approximately 19 Wh per pulse.

A small sample of the heat meters were calibrated in the laboratory and were found to have a typical over-read of about 5%. This is most likely to be due to blocking of a small calibration hole in the turbine with dirt. The heat meters are really designed for use with filtered water.

### 16.3.4 Gas meters

Standard domestic gas meters (nominal error up to ±4%) were used to measure gas consumption, modified to give a pulse output. The method of providing the pulse output is shown in Figure 16.9. A brass cam-wheel with 10 teeth was glued to the spindle which normally rotates the small red pointer once per cu. ft. of gas consumed. This operated a micro-switch giving a contact-closure once per 0.1 cu. ft. of gas. The data logger signal conditioning cards were able to count these contact closures as pulses.

In addition to the Gas Board meter, two extra meters were installed in each house - one to measure total gas and one to measure cooking gas (if any).

### 16.3.5 Electricity meters

Standard domestic electricity meters were used, again modified to give a pulse output to the data loggers. The pulses were generated by an infra-red reflecting opto-switch (available from Radio Spares) mounted above the rotating aluminium disc of the electricity meter (see Figure 16.10). A black stripe (already on the disc) interrupted the reflected infra-red beam once per revolution, giving a +5v pulse, counted at the data logger. The circuit for producing the pulses is shown below:

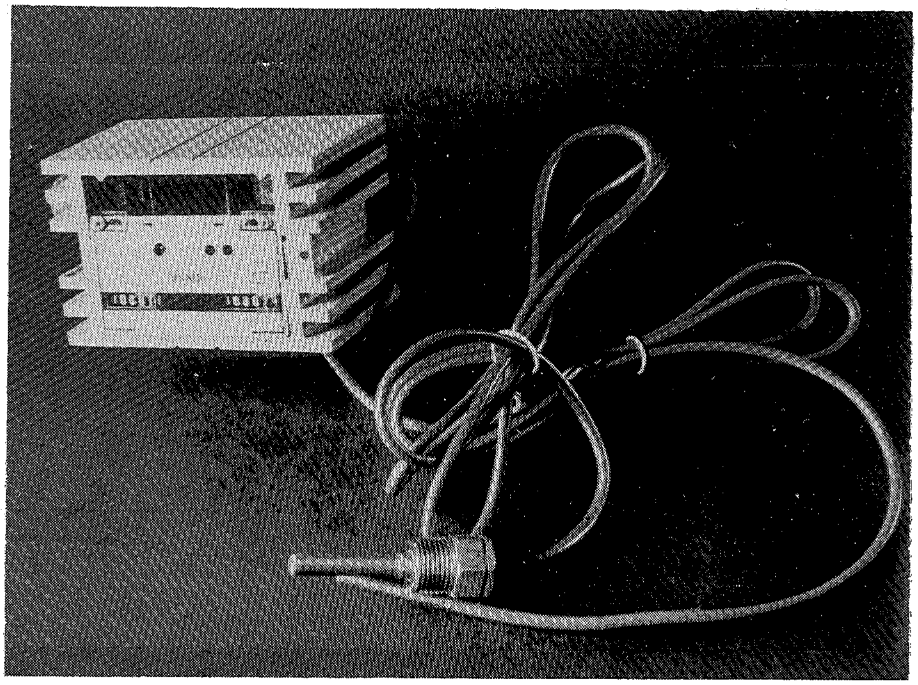


Figure 16.6 Kamstrip-Metro heat meter, showing a temperature probe and its brass housing, and the "head" containing the integrating electronics

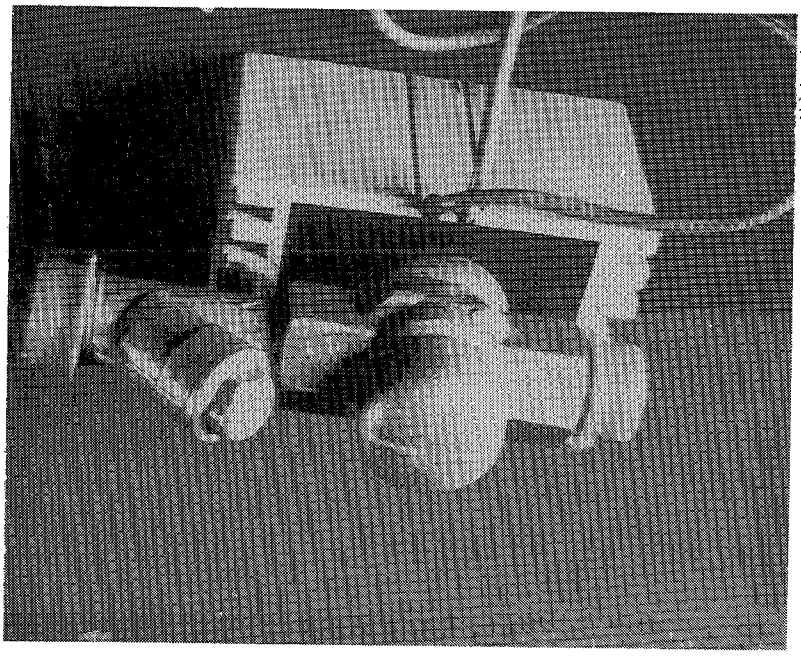


Figure 16.7 Rear view of heat meter showing brass housing for turbine flow meter and temperature probe socket

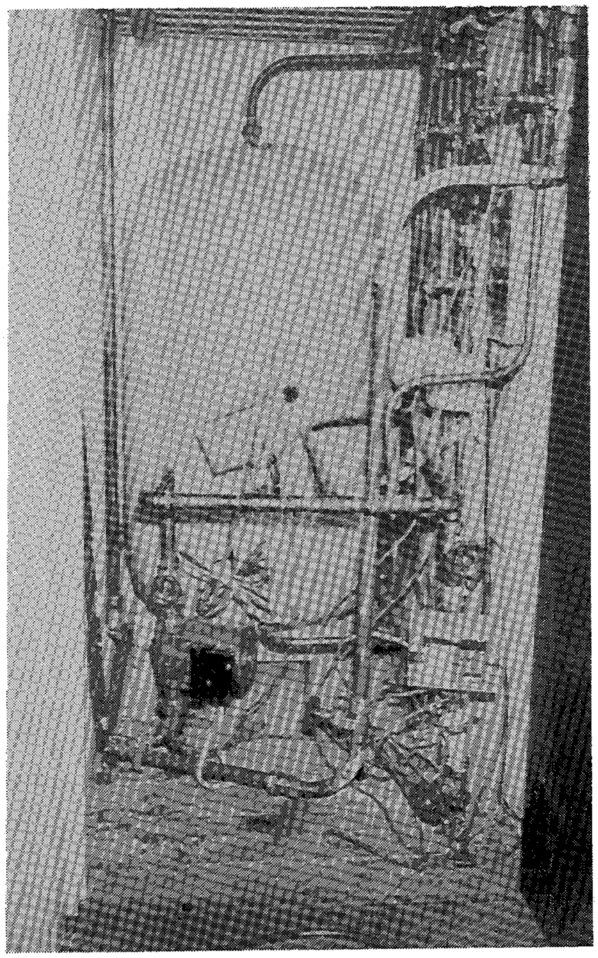


Figure 16.8 Two heat meters installed in an airing cupboard, one for space heating (right) and one for domestic hot water (in front of cylinder, angled).

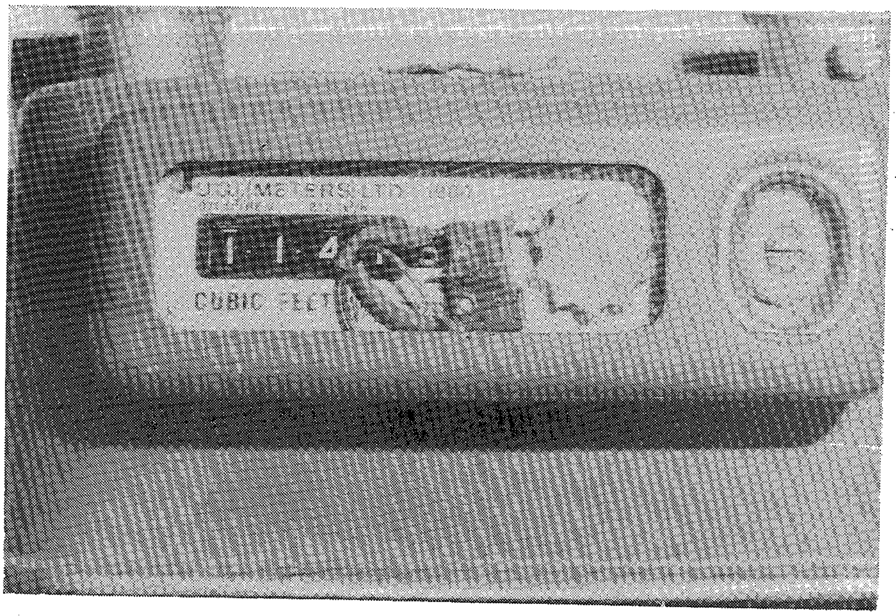


Figure 16.9 Modification to gas meter to provide pulse output (one pulse per 0.1 cu. ft.). The brass cam-wheel attached to the spindle (part of the gas meter) rotates, operating the micro-switch

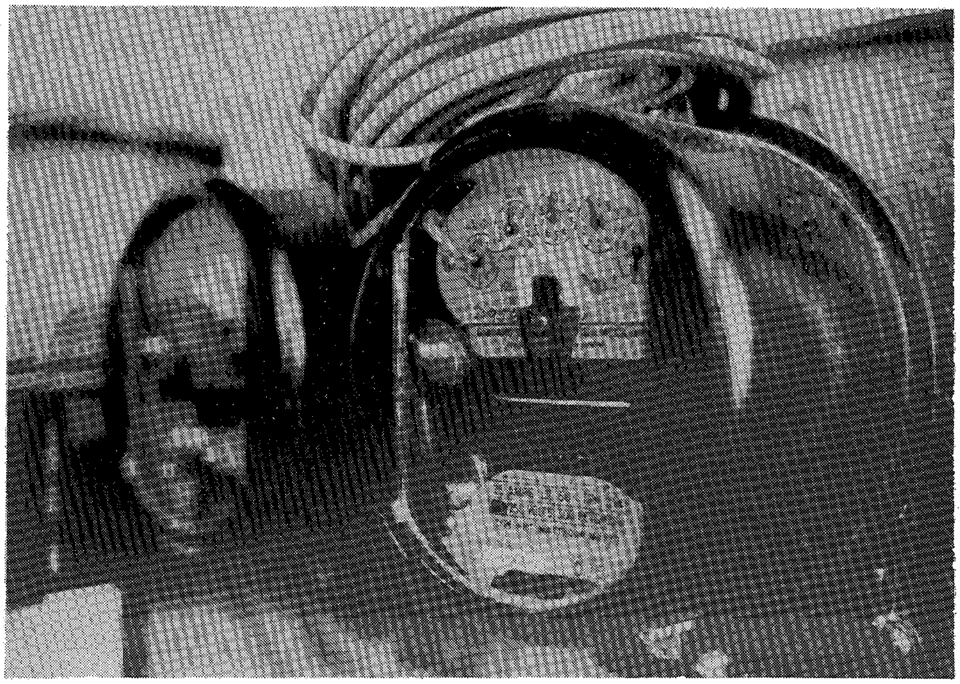
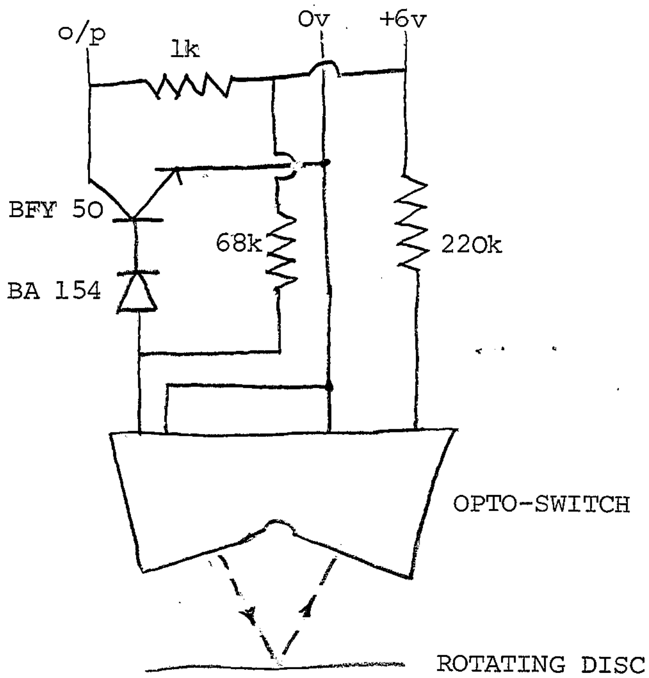


Figure 16.10 Modification to electricity meter to provide pulse output (300 pulses per kWh). An infra-red reflecting opto-switch is mounted above the rotating aluminium disc. The reflected beam is interrupted once per revolution by a black stripe on the disc




The disc rotated 300 times per kWh, thus the resolution was 1/300 kWh.

16.3.6 Window and door switches

(i) Doors

Sensors installed to monitor door openings (though they were never used), were magnetic proximity switches. These consist of two components: an encapsulated reed switch and an encapsulated magnet (Figure 16.11).

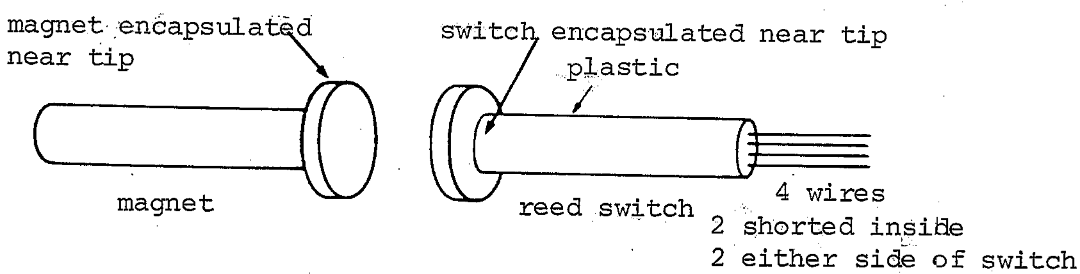



Figure 16.11 Magnetic proximity switch for monitoring door opening

The magnet was recessed in the top edge of the door, and the switch recessed in the door jamb or frame, at a point that is directly above the magnet when the door is closed. As the cable was laid to the door frame during the construction of the house, everything was concealed and hardly visible.

When the magnet is in close proximity to the switch (i.e. when the door is closed), the reed switch will be in the closed position and as the door is opened, the disappearance of the magnet releases the reed switch to its open position. The magnet will begin to operate the switch when they are about 10 mm apart.

Although these sensors were installed and tested, they were never used, due to lack of recording capacity on the data loggers.

(ii) Windows

The sliding panes of the windows were monitored using lever-action micro-switches (Figure 16.12). These were screwed to the top and bottom edges of the window frame. Three switches were used for each window frame, to monitor each of the three opening panes.

The switches were encoded using binary-coded-decimal notation (BCD) on the data logger. This is illustrated in Figure 16.13. Each data recording consists of four digits from 0-9. The BCD cards used in the data loggers convert the 3-bit binary number (generated by three switches connected to the input), into its corresponding decimal number. Thus each digit of a 4-digit data entry can encode three switches, making a total of 12 switches per BCD card, which occupies one channel in the data logger. This is equivalent to 4 window frames. For each house, 11 window frames were monitored, thus three channels were necessary for each house.

The example in Figure 16.13 shows how 12 switches are encoded to give a decimal data entry of 4376 on one channel in the data logger.

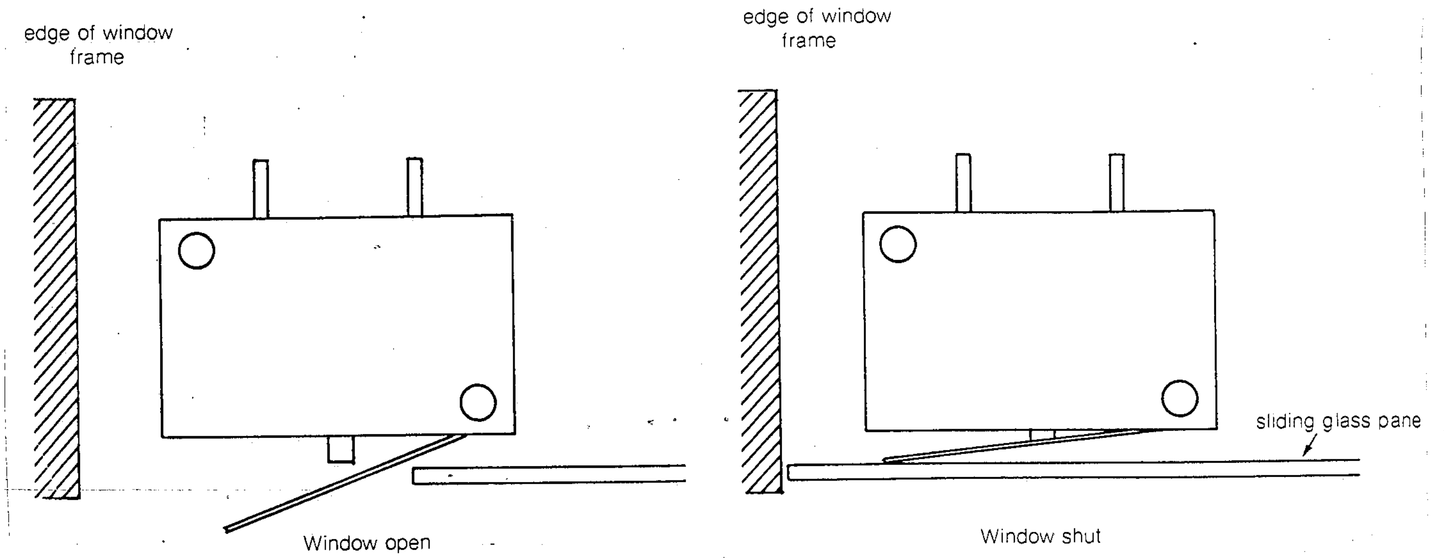
It is very important that every single switch is tested, as this makes the difference between a window being registered as open or shut. When using such data to estimate ventilation rates (Chapter 9), data errors would compound the already considerable uncertainty present in the method of estimation.

The switches were tested by operating each switch in turn, by opening and closing individual window panes, and observing the recording on the data loggers. As the data loggers were situated in the test house garage, and the switches were anything up to 100m away, this involved two people, one at each end, in contact over a walkie-talkie system. This greatly assisted the testing process.

### 16.3.7 Programmer status

It had been intended to monitor the status of the central heating programmer, to be able to differentiate between times when the heating system was off due to the time clock being off, and times when the thermostat was satisfied.

A number of relays were connected in parallel with such components as the time clock and space heating and hot water motorised valves. However, these were not used due to lack of time to complete connections at the test house, and lack of recording space.



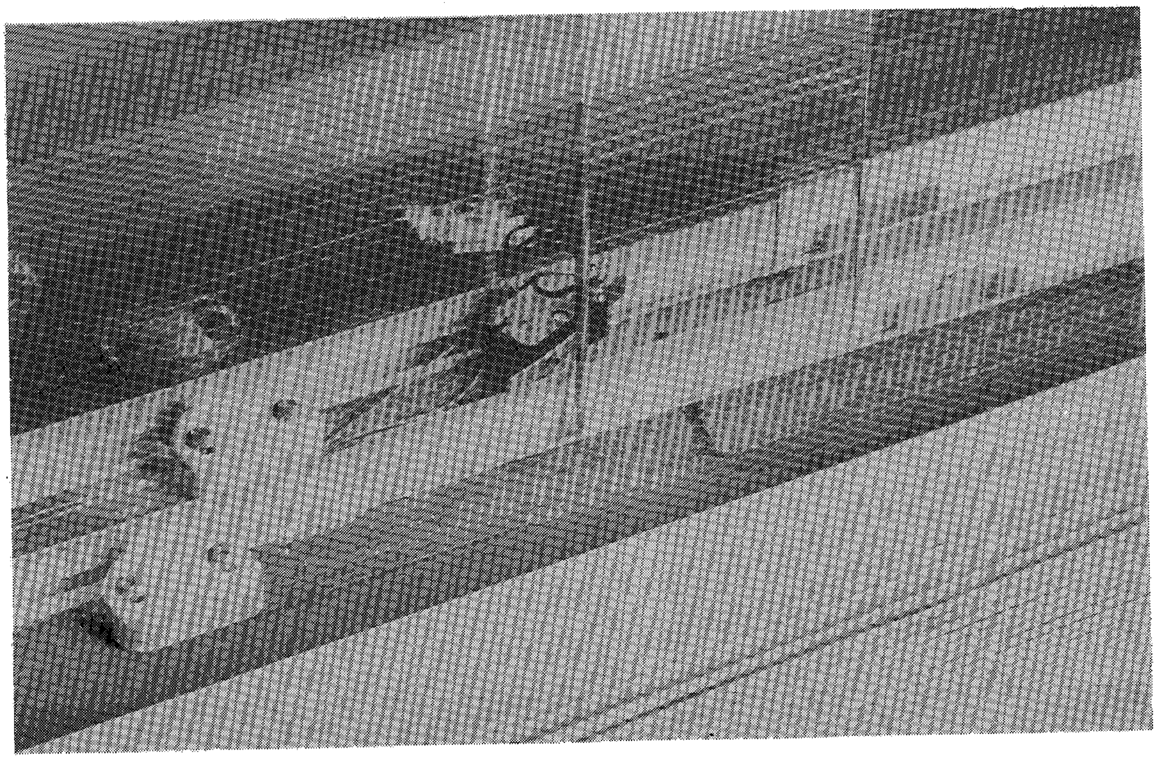



Figure 16.12 Lever action micro-switches were used to monitor window openings

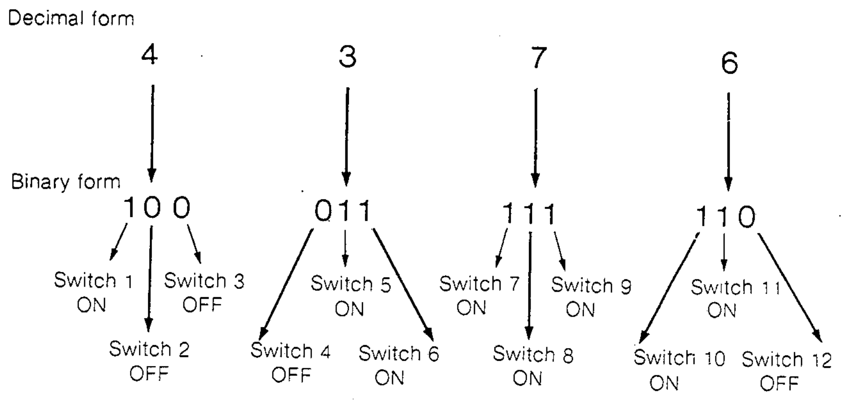



Figure 16.13 The switches were encoded in binary form

16.3.8 Solar radiation measurements

Global solar radiation was measured on horizontal and vertical south-facing surfaces using Kipp and Zonen solarimeters. These are thermopile-type instruments and have become widely used and accepted in many field trials. Outputs are typically 11-13 mV per kWh/m$^2$.

They are not strictly designed for measurements on vertical surfaces, but the errors involved are small and can be considered negligible for the purposes of the project.

The instruments were mounted at the top of a 10.5 metre high mast erected in the test house garden (Figure 16.14). This mast could be lowered for maintenance purposes (Figure 16.15).

The millivolt output from the solarimeters was integrated using an integrating circuit designed and built at the Open University. This was basically a voltage to frequency converter, giving an output of 1000 pulses (+5V) per hour for an input level of 10 mV (equivalent to about 800 W/m$^2$, which is close to the maximum solar radiation intensity in the U.K.). A data logger recorded the pulses received every 5 minutes. Each instrument was calibrated at the beginning, middle and end of the two year monitoring period.

16.3.9 Wind measurements

(i) Anemometer

Wind speed was measured using a rotating-cup anemometer. This was designed and built by the Reading University Department of Meteorology, based on a commercial design by Vector Instruments Ltd. It used a sensitive 3-cup head.

The output was in the form of a pulse-train, the pulse rate being proportional to wind speed.

(ii) Windvane

A lightweight windvane also manufactured at Reading University, was used to monitor wind direction. This had a 5 bit parallel Grey-code output, giving a resolution of 11.25$^\circ$ (32 points on the compass).

For the first 9 months of monitoring, the output was coded using a BCD-type input channel, similar to the window switches. However, the instrument failed repeatedly during this period. Eventually, the instrument was modified at the OU to give an analogue output of 0-360 mV, after which it functioned reliably.

Both instruments were mounted on the weather mast, with the solarimeters (Figure 16 .14).

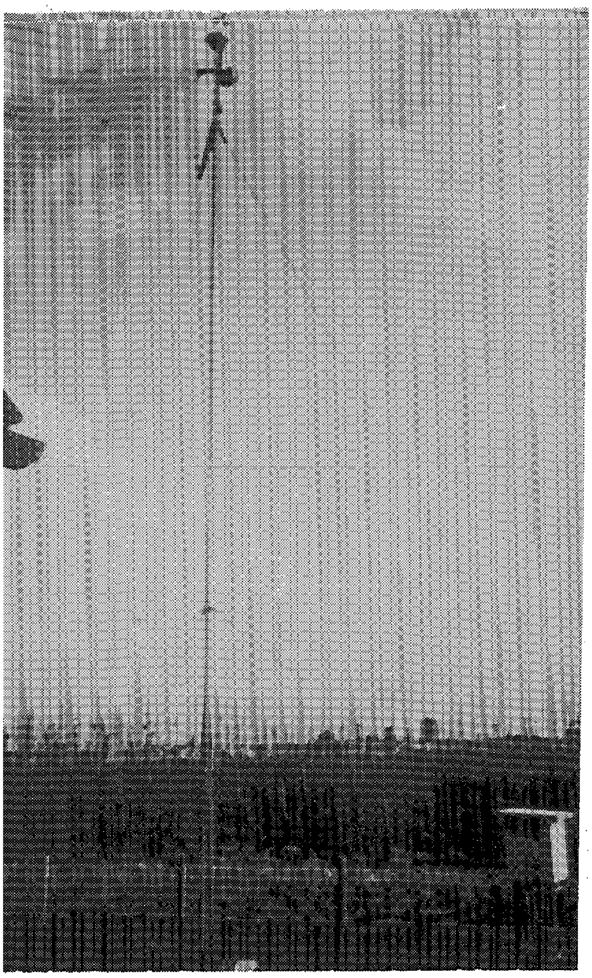


Figure 16.14 Weather mast in test house garden, showing solarimeters, anemometer and wind vane

Figure 16.15 Researchers attempting to remain cheerful while maintaining weather mast

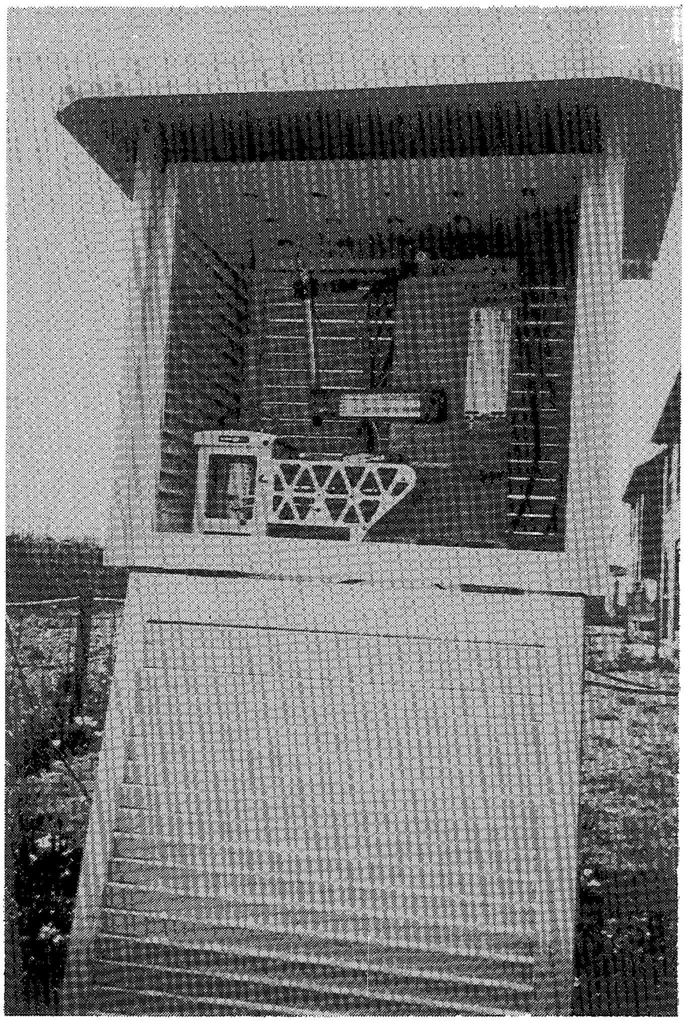


Figure 16.16 Stevenson screen in test house garden, containing PRT sensor connected to data logger in garage, thermograph and max/min thermometers and humidity sensor

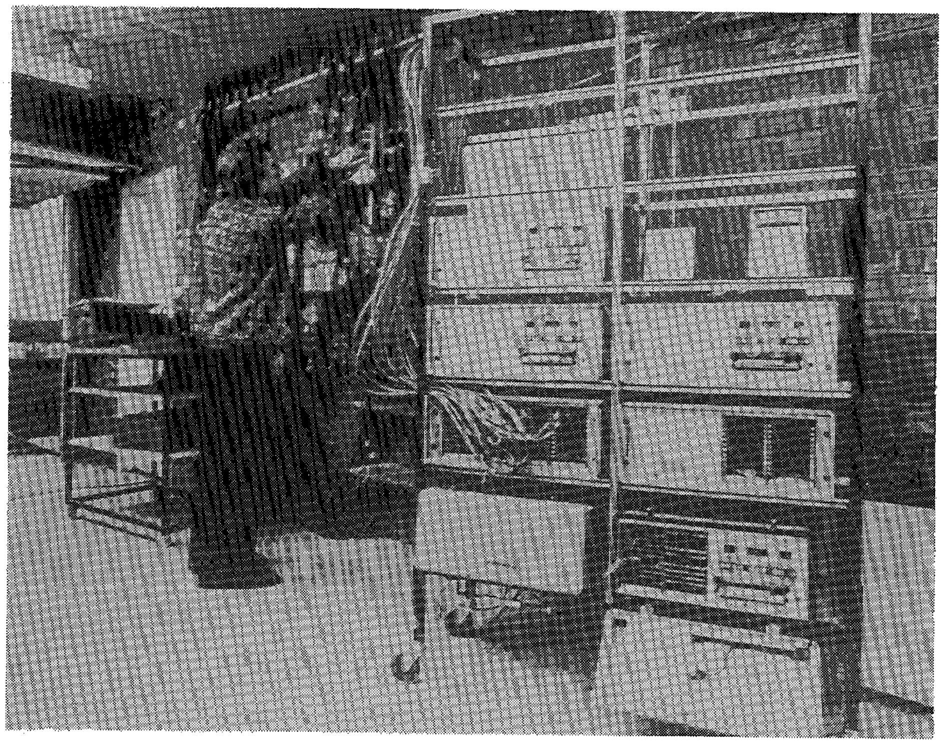


Figure 16.17 Data logging equipment in test-house garage. All the multi-core cabling from the houses terminated at "patch-panel" type junction boxes on the wall. Standardised multi-channel converter cables then connected combinations of sensors to the loggers, rather like a telephone switch-board

### 16.3.10 Humidity

A Vaisala HMP 21 U Humidity probe was used to monitor external relative humidity. This used an integrated circuit device sensitive to moisture levels. Output was in the form of an analogue voltage between 0 and 100 mV.

### 16.3.11 External air temperature

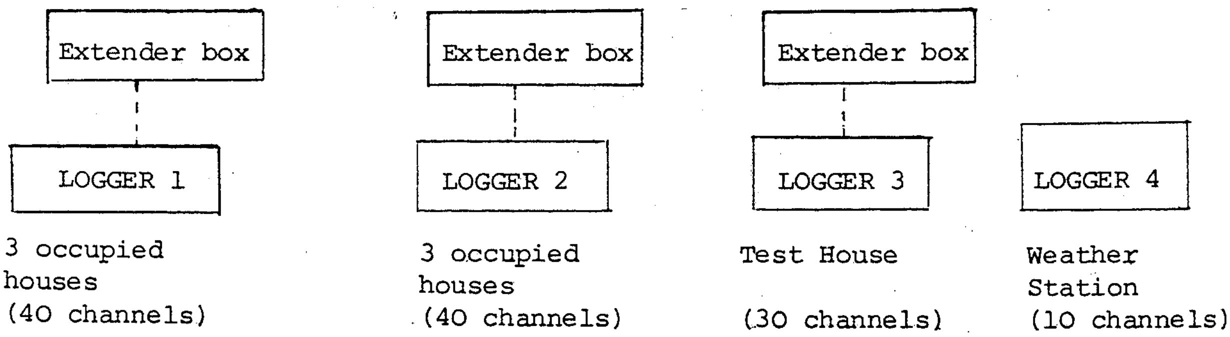
This was measured using a PRT as for the internal temperatures. The sensor was positioned inside a Stevenson Screen in the test house garden (Figure 16.16), together with other temperature recording instruments such as a thermograph, the humidity sensor and manual thermometers. These were used to provide back-up data for use when the data logging equipment failed temporarily.

### 16.3.12 Data loggers

Four Microdata M1600 data loggers were used to record the data. These were situated in the test house garage (Figure 16.17).

The M1600 is a versatile logger, which can accept up to 20 mixed analogue digital or pulsed inputs. They can be expanded to up to 100 channels using extender boxes.

The arrangements for long-term monitoring are summarised below:




The loggers are mains-powered with self-contained rechargeable batteries floating on the power supply.

Scan periods from 10 ms to 99 hrs are possible, data being recorded on 4-track tape cartridge.

### 16.3.13 Ventilation rate measurement

To supplement the detailed measurements carried out by British Gas over a two week period in November 1982, a relatively simple measurement system was developed at the Open University which could carry out sequential measurements of the whole house infiltration rate in the test house unattended for up to 24 hours.

The system used Nitrous Oxide ($N_2O$) as a tracer gas and an IRGA 120 Infra Red gas analyser (manufactured by Sieger Ltd.), to monitor the internal concentration of $N_2O$. The measurement was based on the decay method, whereby the tracer gas is first distributed uniformly throughout the house at a concentration appropriate to the analyser (about 100 ppm). This was done by releasing the gas into each room via thin nylon piping, and mixing the gas with the air using electric fans.

Once the gas supply is turned off, the rate of change of concentration c with t is then measured with the gas analyser, by sampling air from all rooms through nylon piping passing through a mixing box.

If v is the flow rate of ventilating air into (and therefore out of) the house of volume V, then the change in tracer concentration in time interval dt is:

$$dc = \frac{-vc}{V}\,dt = -Acdt$$

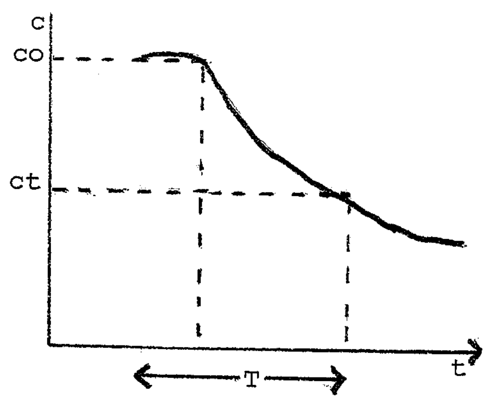
where A is the air change rate in house volumes per unit time,

therefore $$\frac{dc}{c} = -Adt$$

and $$[\ln c]_{co}^{ct} = -A[t]_{o}^{t}$$

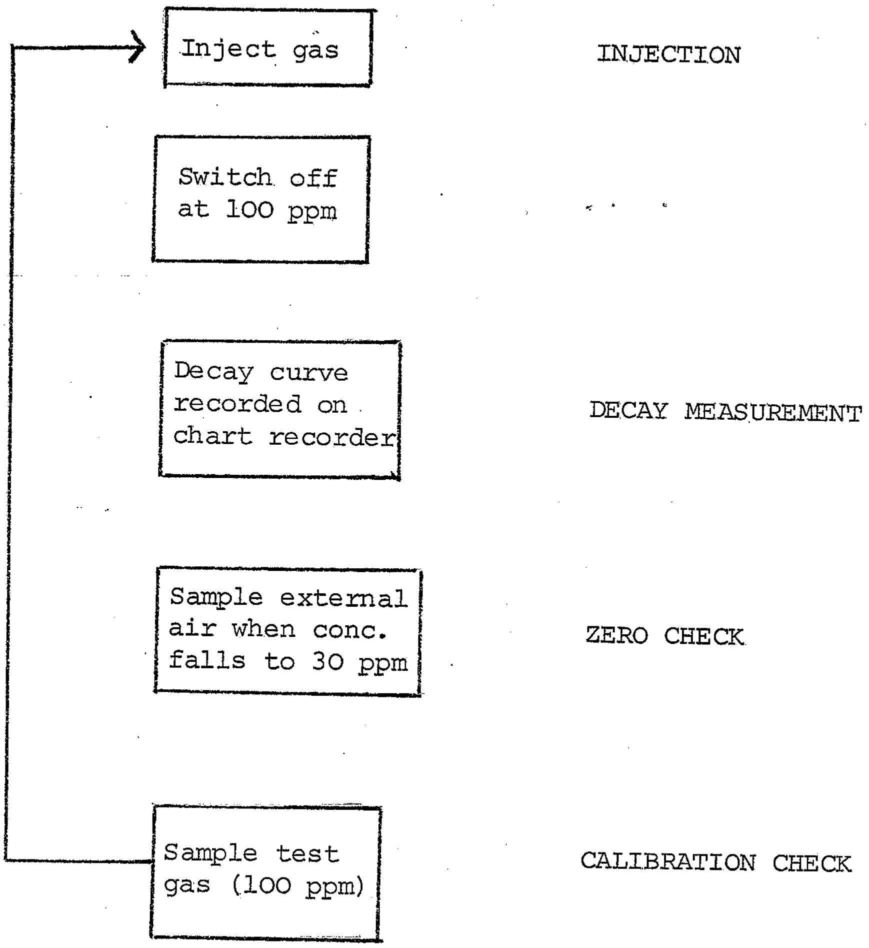
and $$\ln\left(\frac{ct}{co}\right) = -AT$$

and $$A = \frac{-\ln\left(\frac{ct}{co}\right)}{T}$$




The air change rate can simply be calculated from two points on the decay curve, as shown above.

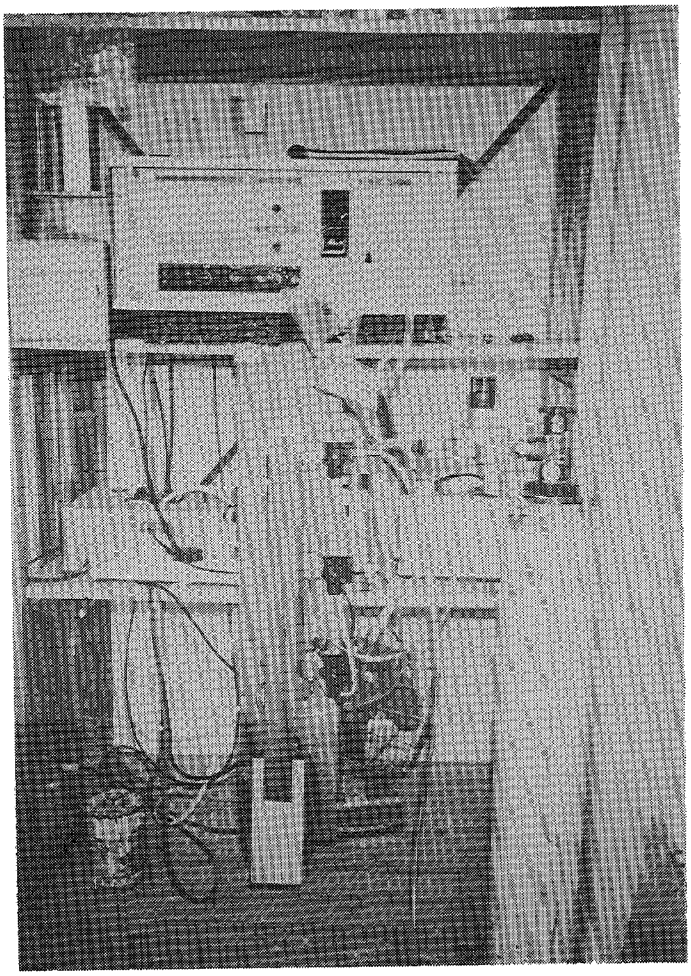
The operation of the OU system was as follows:



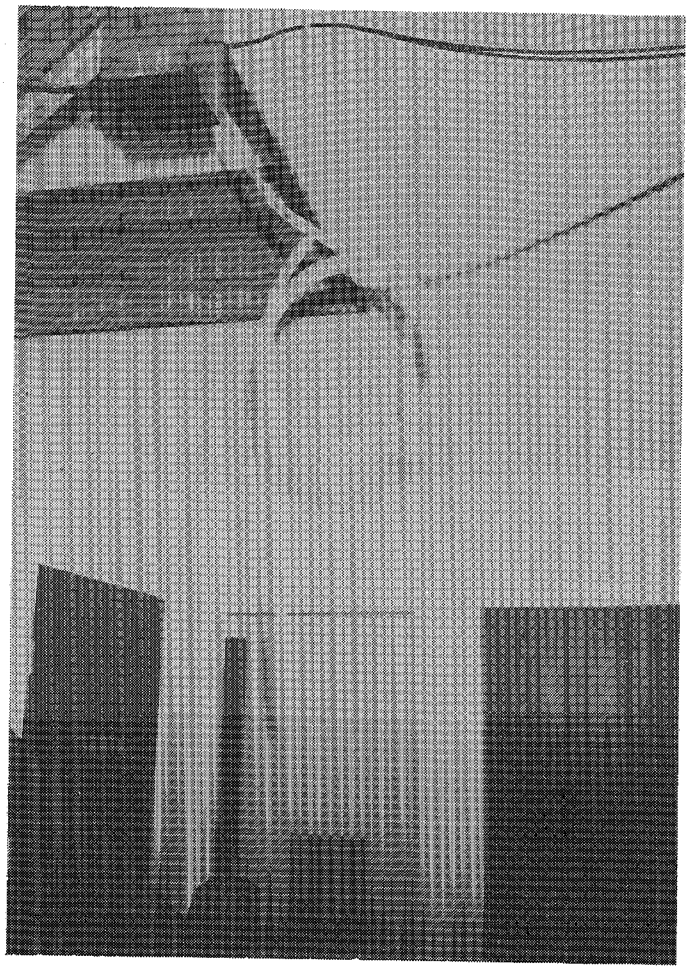

At the end of each decay measurement, air from outside the house was pumped through the system for about 15 minutes to act as a zero check, followed by a calibration check using a test gas containing 100 ppm $N_2O$/air mixture. This was necessary due to the slow, continuous calibration drift of the gas analyser.

At all times, the air was drawn through silica gel crystals to remove moisture which would affect the measurements. This needed changing every 24 hours.

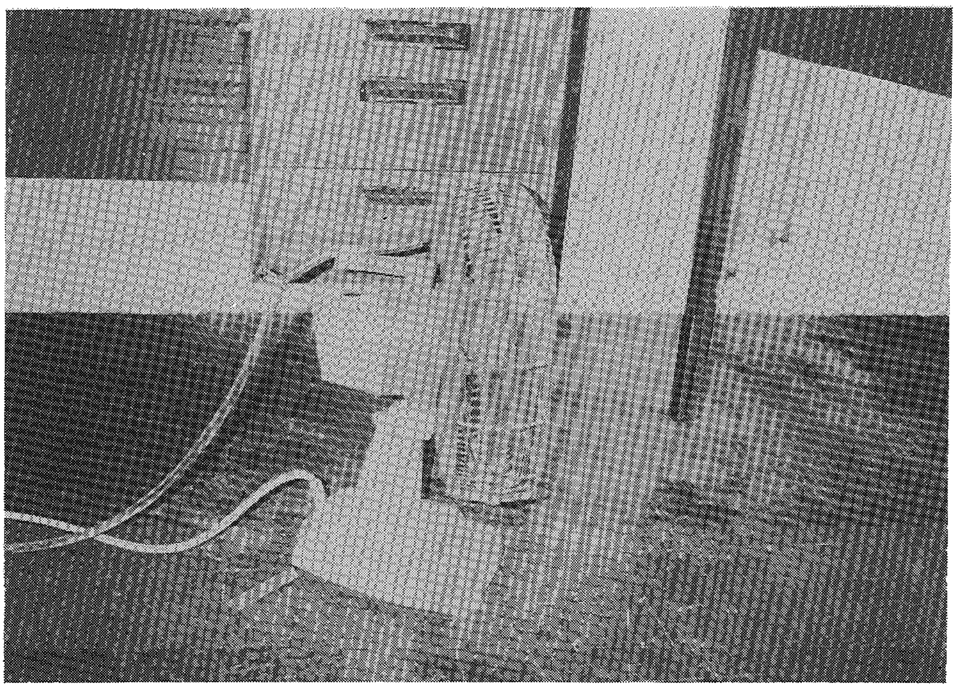
The apparatus used is shown in Figure 16.18, and a typical decay curve is shown in Figure 16.19.



Gas analyser, gas supply, controllers and chart recorder

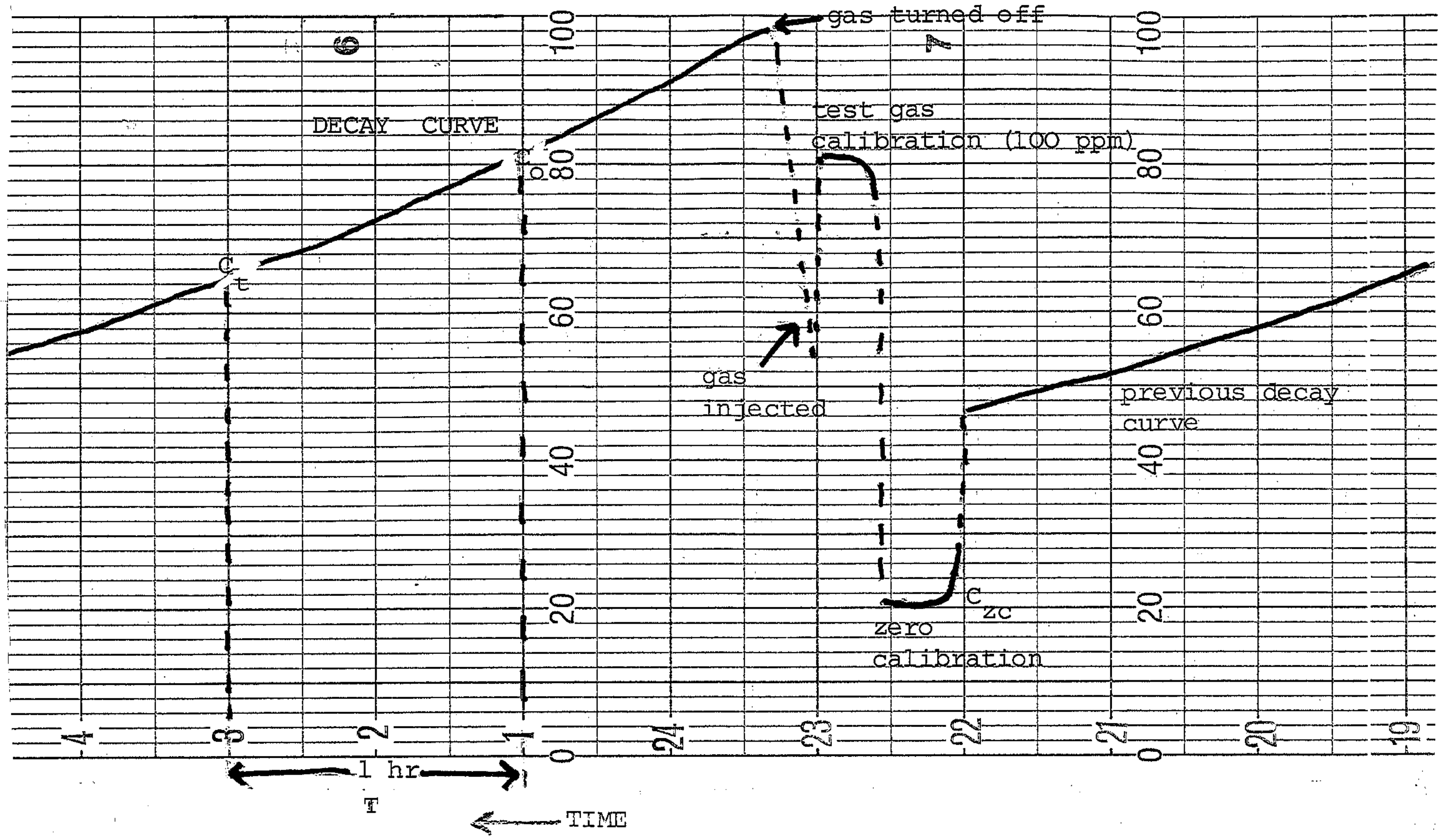


Air is sampled for its $N_2O$ content through nylon tubes in each room. This one has a small flow meter attached.



$N_2O$ gas is injected into the air, using fans to achieve a uniform mix

Figure 16.18 Ventilation rate measuring equipment




$$\text{Air change rate} = \frac{-\ln\left[\dfrac{(C_t - C_{zc})}{(C_o - C_{zc})}\right]}{T} = \frac{-\ln\left[\dfrac{(65 - 21)}{(82 - 21)}\right]}{1}$$

$$= 0.33 \text{ air changes per hour (ac/h)}$$

Figure 16.19 <u>Typical decay curve from ventilation rate measurements</u>

## 16.4 Installation of monitoring equipment

All sensors inside the houses were installed during their construction. This was done in two phases. The site electrical contractors fitted all the internal cabling (4-core screened) to the sensor points, leaving a short length exposed for connection of the sensor at a later stage. This was done by OU technical staff. All the cabling was laid to the external meter cupboard, where they were later connected to a large terminal board. From this terminal board, 20-core screened cable led back to the test house garage via 6" plastic drainpipe buried to a depth of 18".

Each house had approximately 70 4-core screened cables leading to the meter cupboard, and 12 20-core screened cables out to the test house. The potential confusion that could be caused by careless labelling of this many cables is frightening. Therefore great care was exercised in ensuring that each cable was reliably labelled, and that the labels would not become detached.

The site electricians themselves devised a very simple and effective way of labelling. Each end of the 4-core cable was labelled as they were laid, by first wrapping a few turns of PVC tape around the cable, close to its end. Then a code number was written in biro on the tape which was then wrapped a few more times around the cable to finish. Thus the code was protected from scuffs, rain, mud etc. by a few turns of PVC tape. When sensors were connected at a later stage, the last few turns of tape were peeled off to reveal the code number.

For the 20-core cable, bunches of 12 cables (corresponding to one house) were cut to length and threaded through the pipes, labelled with the house number at each end. Each cable within the bunch of 12 could be later identified by continuity testing.

Using these simple methods, the installation of cabling was a great success with no mislabelling at all. The only casualty was in the 20-core cable for one house. Two out of the twelve cables had been cut too short and underground junctions were required to complete the length. This was not carried out due to lack of time.

Figure 16.20 shows the external meter cupboard of an occupied house, containing the extra gas and electricity meters, and terminal board. At the test-house end, the 20-core cables were hard-wired to junction boxes (one per house) fitted with 5 pin din sockets (one per sensor) for temperatures and gas and electricity consumption etc., and multi-pin sockets for the window sensors.

Standardised leads were constructed with 10 5-pin din leads at one end, and a 40 pin multi-pin connector at the other for connection between the junction boxes and the data loggers.

Pin configurations were chosen such that the individual sensor leads (5-pin din plugs) inserted in the junction boxes were interchangeable between sensor sockets on the junction box, requiring only a change of signal conditioning card in the data logger if the type of sensor was different (e.g. temperature switched to gas consumption). The adapter leads themselves were interchangeable between data loggers.

This arrangement was rather like a telephone switchboard, or "patch-panel" and allowed a high degree of flexibility in choosing combinations of sensors,

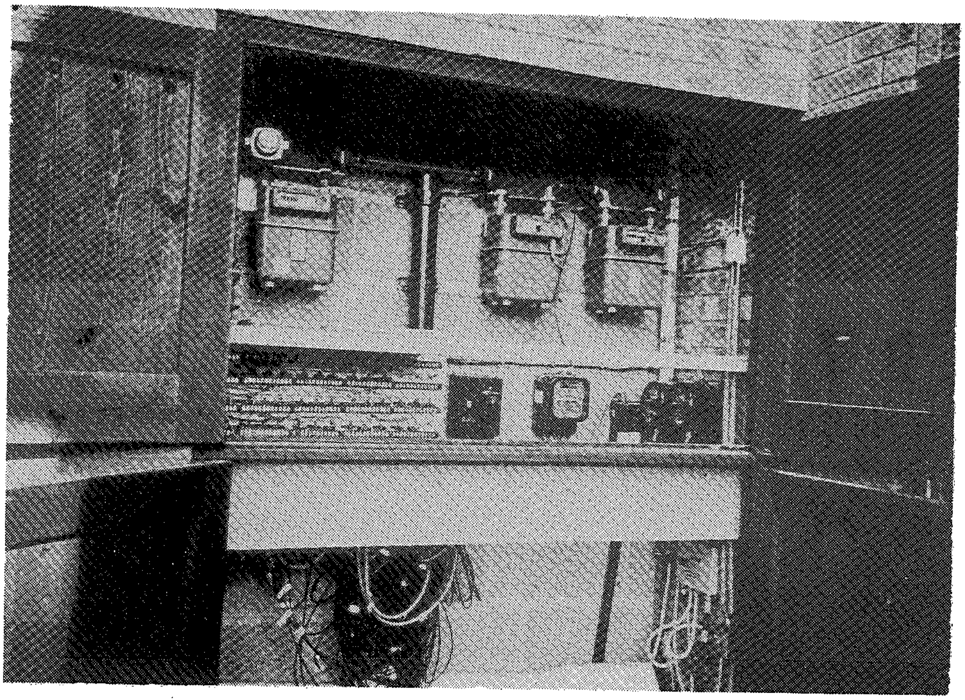


Figure 16.20 External meter cupboard (occupied house) showing two extra (modified) gas meters (to the right), two extra electricity meters (to the right of main meter), and cabling terminal board

and switching of sensors between data logger channels when faults arose.

Figure 16.17 shows the data loggers and some of the wiring in the test house garage.

## 16.5 Problems, reliability, maintenance

### 16.5.1 Commissioning

Once the monitoring equipment had been installed, there followed a lengthy process of commissioning, leading to routine data collection. This commissioning period took several months, but included making all soldered connections at the external meter cupboards and the test house garage. The amount of time and effort involved in commissioning an off-site monitoring system of this size and detail, in order to achieve routine, reliable data flow, should never be underestimated.

### 16.5.2 Noise

One constant problem that could only be relieved rather than removed was that of noise, in the form of mains hum and RF pick-up. This was despite careful attention paid to adhering to a star-earth system. There seemed to be a substantial level of RF noise picked up via the ground, seemingly through the earth rod used for the cabling. This was relieved where necessary using filters.

### 16.5.3 Reliability of instrumentation

Most of the sensors worked reliably. However there were some notable exceptions.

The PRT's embedded in structural elements for surface temperature measurements either did not work at all or suffered intolerable noise problems. Those that did not work were presumably damaged when embedded in wet concrete or plaster, probably through insufficient protection of soldered connections. The same noise problems existed for the embedded heat flux meters. It seemed that any sensor that was in good contact with the ground or a wall attached to the ground suffered from high levels of mains hum and RF noise. Presumably, a large earth-loop had been created which, for all the efforts of researchers and technicians, could not be broken. As a result, none of the surface temperature measurements and heat flux measurements in the occupied houses were of any value. Only the heat flux measurements in the test house were successful. This was a considerable disappointment in hindsight, as the floor heat losses turned out to be much higher than expected; more data, especially in the occupied houses, would have been valuable.

The heat meters, after modification to provide pulse output, performed reliably. The only maintenance required was the routine washing of the turbine flow meter and replacement of batteries (both carried out once per year). This was not, however, the experience of Pennylands, where turbines frequently jammed due to sludge deposits, causing a large maintenance problem. It is not clear why they should be any worse at Pennylands; possibly more sludge deposits were generated within the Pennyland heating systems than Linford.

The modifications to the gas and electricity meters proved reliable, with only the occasional failure for the gas meter. The failures were due to the brass cam-wheel becoming detached from the spindle (they were glued on), and they were quickly repaired. However, failures can only be noticed by regular inspection of the data. This can be done by either inspecting a batch of data immediately it has been transferred to the computer, or by inspecting the previous recorded values displayed on the data logger monitor screen. The latter is particularly useful as data logger faults can be quickly spotted.

Once fully tested, the window switches were completely reliable.

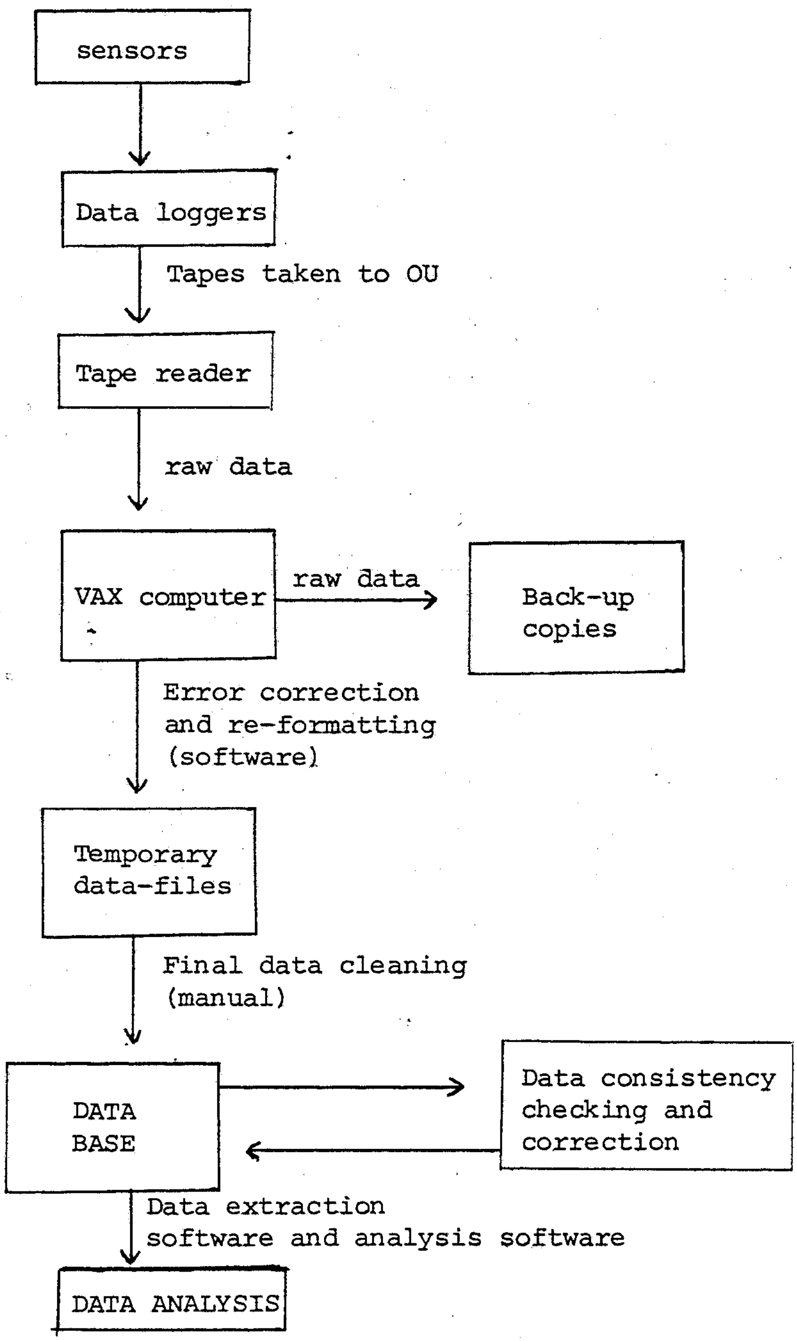
The Kipp and Zonen solarimeters gave no problems and were calibrated at the beginning, middle and end of the monitoring period. The digital-output wind vane was very unreliable for the first year, and no useable data was obtained. After being modified to give an analogue output it functioned reliably.

Some display and control cards malfunctioned, but these were quickly replaced. The tape heads needed to be cleaned regularly to ensure reliable data recording.

Considering the huge number of soldered joints in the monitoring system, very few problems due to dry-joints were encountered.

## 16.6 Data collection, storage and processing

The various stages of data processing, from recording the data to constructing a fully processed data base is summarised below:



### 16.6.1 Data collection

The bulk of the data was, of course, recorded on the data loggers. However, certain data were recorded manually as back-up. This included gas and electricity meter readings from the occupied houses and test house, daily maximum and minimum external air temperatures, and a summary of weather conditions based on visual observations (e.g. cloud cover, approximate wind speed and direction, occurrence of rainfall, fog, frost etc). Also, a record was kept of the use of blinds and curtains in the occupied houses. This was done as a visual check once per week-day at about 10 a.m.

For the data recorded on the data loggers, 15 minute scan periods were used for the occupied houses and test house, and 5 minute scan periods for the weather station.

For the number of channels and scan frequency used, each track could record up to 10 days data. Tapes were usually changed every 7 days.

### 16.6.2 Data transfer

The tapes were read into a VAX 11/750 computer using first a Perifile Sintrom tape reader which was later replaced with a Columbia reader. The Columbia was considered superior in every way to the Sintrom.

This process was relatively trouble-free but it was found that considerable data corruption could result from attempting to read the data at too high a speed (baud rate). At 9600 baud error rates could be up to 2% of all data, which is huge. On reducing to 2400 baud, error rates were negligable - usually less than 0.05%.

Once the minitoring system was working routinely, minor gaps in data caused by a variety of minor faults and unavoidable delays in changing tapes, usually totalled less than half a day per month. Occasionally gaps occurred for one or two days at a time due to a failure that was not noticed immediately. The most serious gaps in monitoring were about two weeks (two occasions), but both were during the summer, when continuous data is less important.

### 16.6.3 Raw data format

Each data entry consisted of eight alpha-numeric characters, of the forms:

(i) N04+0203 - channel number 4, +20.3°C

(ii) N08*1723 - channel number 8, 1723 pulses recorded

(iii) N19*3510 - channel number 19, decimal number 3510 encoding up to 12 switches as used to monitor window openings.

The first three channels of data give timing and identification information:

N00*0001 - day number 1

N01*0330 - time 0330 hrs

N02-0001 - logger number 1

The rest of the data string up to the next occurrence of these three channels are relevant to this time, i.e. day 1, 03.30 hrs.

The data is recorded directly onto the tape in the form of a single, very long string of individual channels. An example of a small file of raw data is given below:

```
N08+0243N09+0238N10+0230N11+0250N12+0243N13*0000N14*0000N15*0000N16*0012N17*000
0N18*0001N19+0236N20+0241N21+0232N22+0238N23+0242N24+0232N25*0000N26*0000N27*00
13N28*0000N29*0001N30+0252N31+0235N32+0236N33+0250N34+0253N35+0254N36*0000N37*0
000N38*0027N39*0000N00*0006N01*0330N02-0001N03*0222N04*0231N05*0227N06*0236N07*
0236N08+0242N09+0245N10+0230N11+0250N12+0242N13*0000N14*0000N15*0000N16*0016N17
*0000N18*0001N19+0235N20+0241N21+0232N22+0237N23+0241N24+0231N25*0000N26*0000N2
7*0017N28*0000N29*0001N30+0252N31+0235N32+0236N33+0249N34+0252N35+0254N36*0000N
37*0000N38*0024N39*0000N00*0006N01*0345N02-0001N03*0222N04*0231N05*0227N06*0236
N07*0236N08+0242N09+0235N10+0230N11+0249N12+0242N13*0000N14*0000N15*0000N16*000
7N17*0000N18*0002N19+0235N20+0240N21+0231N22+0236N23+0240N24+0230N25*0000N26*00
00N27*0019N28*0000N29*0001N30+0251N31+0234N32+0235N33+0249N34+0252N35+0254N36*0
000N37*0000N38*0014N39*0000N00*0006N01*0400N02-0001N03*0222N04*0230N05*0226N06*
0235N07*0235N08+0242N09+0257N10+0228N11+0252N12+0242N13*0000N14*0000N15*0000N16
```

16.6.4 Formatting and error correction

The data is fairly useless in this form. A program was developed to re-format the data into a more legible form, and to identify and correct (where possible) bad data.

An example of a bad data entry might be:

NO*0206 - where it would appear that a digit from the channel identification has been dropped. The program spots this, deduces the correct channel number by reference to the proceeding and following channel numbers, and inserts the correct data entry.

Other examples of bad data are:

26*0000 - should be N26*0000

N13* 013 - should be ?

In the latter case, a digit has been dropped from the data value, but it might have been dropped from the beginning, end or middle of the digit string. In this case the program compares the value recorded with the average and standard deviation of previous values for that channel number, and attempts to replace the missing digit such that the corrected value is within one standard deviation of the average (calculated from the previous recorded values for that channel). If this is not possible, the data entry is discarded.

Particular attention is paid to the timing channel, channel no. 1. If this is missing or corrupt, then all the subsequent data entries for that time-slot will have no place in the eventual database, as this is organised on a chronological basis. Therefore it is important that all recordings of channel 1 are present in the re-formatted data before it is appended to the data base.

An example of the error messages that are generated by the correction program is shown below:

```
Total records read = 20483

Channel Number    Mean  Std.dev Normed
         read                   std.dev
  00      512 DAY        Min    0 Max   11
  01      514 TIME INCREMENT    0.6 mean errors  0.6
  02      511 LOGGER ID    -0    Bad -10000
  03      511    223.11   0.88    0.00
  04      511    230.07   0.23    0.00
  05      511    223.67   0.08    0.00
  |        |        |       |       |
  |        |        |       |       |
  |        |        |       |       |
  35      512    250.55   0.16    0.00
  36      512      4.97   9.10    1.83
  37      512      0.00   0.00    0.00
  38      512     39.34  20.87    0.53
  39      511      8.19  13.81    1.69

Total records ok = 20483, 100.000%

Line       1  bad sequence    predict 00      real     08
Line     553  last time >= current    day     7        time     0      2345
Line     865  bad sequence    predict 32 <=   real     24
Line    1187  last time >= current    day     8        time     0      2345
Line    1827  last time >= current    day     9        time     0      2345
Line    2467  last time >= current    day    10        time     0      2345
Line    3107  last time >= current    day    11        time     0      2345
Line    3414  bad sequence    predict 39      real     00
Line    3414  bad sequence    predict 02 <=   real     01
Line    3414  last time >= current    day    11        time  1130      1130
Line    3414  bad sequence    predict 02 <=   real     01
Line    3414  last time >= current    day    11        time  1130      1130
Line    3414  NO2 av    -1.00 sd -10000.00             Line     3414   last
                   time >= current    day    11        time  1130      1130

Final number ok = 20484, 100.005%
```

The first part of the error message output gives statistical information on the data, such as the number of entries read, and the mean and standard deviation, for each channel. This is useful in seeing whether any particular channel is suspect e.g. only half as many entries were present as others, or large standard deviations are present in data that is known to be slowly changing (e.g. certain internal air temperatures).

The second part lists information on corrections made or suspect data sequences. The long, single string of data values has been re-formatted into lines of fixed length, and suspect data is listed line by line. For example, in line 1, the program expects to see the first entry as channel 00 (day), followed by channel 01 (time), followed by channel 02 (logger identification), followed by all the data for that time-slot. In fact, the data begins with channel 08, which is a temperature recording. Subsequently, a "bad sequence" error message warns of this. In this case, this is due to the data having been recorded on track 2 of the tape cartridge, after track 1 had been filled.

In line 865, there is another bad sequence - channel 24 follows channel 32. This will require further investigation, as it suggests that a section of data (between channel 01 and channel 23) is missing, and the data from channel 24 onwards has no time identification.

In lines 553, 1187, 1827, 2467 and 3107, the program is identifying "tick-over" on the day channel when the time goes from 23.45 (day n) to 00.00 (day n+1). These are not errors, but their identification is very useful in checking that all the data is present.

The various error messages for line 3414 correspond to the end of the data file, where data has been repeated due to a combination of "logger-bounce" at the end of the recording, and a bug in the correction program which sometimes duplicates the last few data entries.

The cleaned, re-formatted data is shown below (first 10 lines):

```
N08+0243   N09+0238   N10+0230   N11+0250   N12+0243   N13+0000
N14+0000   N15+0000   N16+0012   N17+0000   N18+0001   N19+0236
N20+0241   N21+0232   N22+0238   N23+0242   N24+0232   N25+0000
N26+0000   N27+0013   N28+0000   N29+0001   N30+0252   N31+0235
N32+0236   N33+0250   N34+0253   N35+0254   N36+0000   N37+0000
N38+0027   N39+0000   N00+0006   N01+0330   N02-0001   N03+0222
N04+0231   N05+0227   N06+0236   N07+0236   N08+0242   N09+0245
N10+0230   N11+0250   N12+0242   N13+0000   N14+0000   N15+0000
N16+0016   N17+0000   N18+0001   N19+0235   N20+0241   N21+0232
N22+0237   N23+0241   N24+0231   N25+0000   N26+0000   N27+0017
   |          |          |          |          |          |
   |          |          |          |          |          |
```

The data file is then manually edited according to the error messages shown earlier, to give:

```
N00+0006   N01+0315   N02-0001   N08+0243   N09+0238   N10+0230   N11+0250
N12+0243   N13+0000   N14+0000   N15+0000   N16+0012   N17+0000   N18+0001
N19+0236   N20+0241   N21+0232   N22+0238   N23+0242   N24+0232   N25+0000
N26+0000   N27+0013   N28+0000   N29+0001   N30+0252   N31+0235
N32+0236   N33+0250   N34+0253   N35+0254   N36+0000   N37+0000
N38+0027   N39+0000   N00+0006   N01+0330   N02-0001   N03+0222
N04+0231   N05+0227   N06+0236   N07+0236   N08+0242   N09+0245
N10+0230   N11+0250   N12+0242   N13+0000   N14+0000   N15+0000
N16+0016   N17+0000   N18+0001   N19+0235   N20+0241   N21+0232
N22+0237   N23+0241   N24+0231   N25+0000   N26+0000   N27+0017
```

In this case, channels 00, 01 and 02 have been inserted (day, time logger no.) at the beginning of the line. Other edits included inserting a missing time channel at line 865 and cleaning up the last few data entries on the last line (3414).

### 16.6.5 Database

At this point the data can be entered into the database, using another program called "append". This program appends the data to the last data entry in the database. The database itself exists in a specially compacted form to occupy the minimum space possible on the computer. This was approximately 30 Mbytes.

A further set of programs were written to extract the data from the database, and perform basic averaging and totalling functions. The main program, called "look" was used in the following way:

e.g. look -l1 -c3 -d100682 +d260682

The resulting output from this would be:

CODE TO IDENTIFY ORIGINAL "LOOK" COMMAND

```
L1 101
10  6 82 03 30  3   222
10  6 82 03 45  3   222
10  6 82 04 00  3   222
10  6 82 04 15  3   221
10  6 82 04 30  3   221
10  6 82 04 45  3   220
10  6 82 05 00  3   220
10  6 82 05 15  3   220
10  6 82 05 30  3   219
10  6 82 05 45  3   219
10  6 82 06 00  3   218
10  6 82 06 15  3   218
10  6 82 06 30  3   218
10  6 82 06 45  3   219
10  6 82 07 00  3   219
```

DAY MONTH YEAR HOUR MINS CHANNEL NO. TEMPERATURE IN 1/10TH'S OF °C

This output could be passed to another program to average over hourly or daily periods, using the Unix operating system "pipe" facility (Section 16.6.7):

e.g., the command

```
look -11 -C3 -d100682 +d260682 | aver -h
```

would give:

```
LmhMs 101
10  6 82  3 03 2 222.00   0.00
10  6 82  4 03 4 221.00   0.67
10  6 82  5 03 4 219.50   0.48
10  6 82  6 03 4 218.25   0.43
10  6 82  7 03 4 220.00   0.65
10  6 82  8 03 4 221.25   1.63
10  6 82  9 03 4 228.75   1.66
10  6 82 10 03 4 227.75   3.13
10  6 82 11 03 4 222.50   1.04
10  6 82 12 03 4 225.75   1.24
10  6 82 13 03 4 225.25   0.80
10  6 82 14 03 4 223.75   2.33
10  6 82 15 03 4 224.25   3.09
10  6 82 16 03 4 222.25   0.90
10  6 82 17 03 4 222.00   0.69
```

DAY / MONTH / YEAR / HOUR / CHANNEL NO. / NO. READINGS IN HOUR / AV. TEMP. IN 1/10THS OF °C / STANDARD DEVIATION

and averaging by day, using the command :

```
look -11 -c3 -d100682 +d260682 | aver -d
```

would give :

```
LmdMs 101
10  6 82 03 82 222.50   3.00
11  6 82 03 95 221.42   6.06
12  6 82 03 96 217.39   2.51
13  6 82 03 96 206.15   5.24
14  6 82 03 96 207.30   6.40
15  6 82 03 96 204.59   4.40
16  6 82 03 96 207.26   5.31
17  6 82 03 96 211.76   8.07
18  6 82 03 96 213.50   6.23
19  6 82 03 96 210.04   2.66
20  6 82 03 96 215.06   6.16
21  6 82 03 94 208.98   3.53
22  6 82 03 95 209.63   9.25
23  6 82 03 94 213.39   3.26
24  6 82 03 93 210.37   2.84
25  6 82 03 92 206.01   2.44
26  6 82 03 96 206.33   2.60
```

DAY / MONTH / YEAR / CHANNEL NO. / NO. READINGS IN DAY / AV. TEMP. IN 1/10THS OF °C / STANDARD DEVIATION

The final stage of data cleaning was to run all the data through filters to identify data values that were outside credible limits. For example, an internal air temperature of $0^{\circ}C$ is extremely unlikely, and is more likely to be a wrong value, either through sensor failure, data corruption on recording or transfer to the computer.

Similarly, a negative reading for gas, electricity or space heating consumption is a nonsense, and should be discarded. By using common sense and pre-conceived notions as to what the practical ranges of the data are likely to be, high and low limits were defined in the filter programs and data entries outside these ranges were identified and stored separately. Then each suspect entry was inspected manually in the database and a judgement made as to whether the entry was correct, whether it should be corrected to a fairly obvious value indicated by previous entries, or whether it should be discarded.

Needless to say, the whole process of data cleaning was lengthy and tedious (several man-months). However its importance is paramount. It is almost pointless proceeding with serious analysis until all the stages of cleaning have been done, as only relatively few ridiculous data entries can cause havoc with averaging and summation, particularly over short periods. Consider the effect, for example, of having a temperature reading of $200^{\circ}C$ instead of $20^{\circ}C$ (quite a feasible error) - the average temperature for that day would be falsely raised by about $2^{\circ}C$.

For space heating consumption data, typical recorded data might be 50 pulse counts in a 1/4 hr period representing about 4 kW steady heat output (1 pulse is equivalent to about 20 Wh). If a single reading were 5000 instead of 50, again a feasible form of data corruption, the daily total would appear to be about 3 times the correct value.

Isolated errors like this may seem insignificant in averages and totals over a whole heating season, or even over a week, but can radically affect the results of regression analysis over relatively short time periods e.g. daily correlations of heating consumption against $\Delta T$ and solar radiation.

## 16.6.6 Computer

The database as described in the previous section, was originally constructed and held on a PDP 11/60 computer using Unix version 6 operating system. This was changed to Unix version 7, and eventually the PDP was replaced with a VAX 11/750 machine running under version 32AV.

These changes caused considerable delay and consternation amongst the researchers, at seemingly having to constantly re-learn operating systems and new system programs. As computer systems change and improve rapidly compared with the length of a housing field trial, this loss of time should not be overlooked at the beginning of a project.

However, it became clear that the larger machine and improved operating system made the subsequent analysis easier and faster.

The entire database was held on disk, so that access was fast, and analysis could be performed directly from the database. In practice many files were created from the database prior to analysis, such as daily averages and totals. Averaging and totalling over long periods was then carried out using these files.

### 16.6.7 Operating system

The Unix operating system (using the "C" language), was found to be most suitable and very flexible for the analysis of the large quantities of data.

One of the most useful and flexible features is the ability to "pipe" the output of one program to the input of another. This can be done several times, so that complicated processes can be built up by stringing together a series of smaller processes or "building blocks". This enables the user to build up a library of smaller programs that are used in various applications. Analysis can proceed by combining these basic programs together, perhaps with small modifications, without having to write large new programs. This process also includes the use of a large number of system programs which are part of the operating system, for use as general software tools.

One of these programs, which was used extensively in the analysis, was a very powerful general purpose pattern-scanning and processing program called "awk". It has its own internal "awk language", which enables the user to manipulate arrays of numbers, character strings, or combinations of both, in just about any conceivable manner, according to mathematical or sorting operations specified by the user in a subroutine or "awk file".

A simple task would be to multiply the temperature data from the database by 0.1 to convert to the correct units of deg. C.

Another would be to search through 1/4 hour data for gas consumption for a whole heating season and to sort the data into pre-determined intervals, to give a frequency distribution of boiler gas input.

Graphical display, essential for effective and efficient analysis, was achieved using the CYCLOPS system (developed by the OU for transmitting electronic images along telephone lines to remote TV monitors), and graph plotting routines already on the VAX as part of the operating system. Hard copy graphs were plotted on a Hewlett Packard A4 plotter.

An example of the use of the Unix operating system in the Linford analysis is shown below:

| look -l1 -c3 -d120682 +d260682 ¦ | aver -h ¦ | awk -f awk.units ¦ | graph.com ¦ | sto |
|---|---|---|---|---|
| Extraction of temperature data from database over 2 days | average by hour | convert to correct units as set in file "awk.units" | convert to graphics instructions set by subroutine in file "graph.com" | output to graphics device (e.g. cyclops) |

This would plot hourly living room temperatures for a particular house over two days on the cyclops display. The correct graph scales, x and y ranges, line colour and style are set in the command file "graph.com". The provision for easy and fast graphical display of the data is essential and its value cannot be over-emphasised. This is particularly true when analysis is at the investigative stage, where the researcher is sifting through the data, looking for interesting events, such as the effect of solar gain in reducing heating demand on cold, sunny days.

### 16.6.8 Back-up data

In addition to the detailed 1/4 hour data recordings on the data loggers, certain measurements such as gas and electricity consumption in the occupied houses were recorded manually, once per week.

Also, external temperatures were recorded on a thermograph, and manually in the form of daily maxima and minima.

Recording back-up data can be extremely useful and important, both as a check on the reliability of the data recorded by the logging system, and as an alternative source of data to fill the gaps in the main database due to equipment failures.

## 16.7 Conclusions from monitoring experience

Although the project as a whole can be regarded as having been carried out with considerable success, there are a number of lessons that can be learned. Many of these lessons can be summed up by the general statement "everything seems to take twice as long as expected and is twice as difficult as first thought". Field trials are notoriously long in duration, and can often present confusing answers at the end.

Some specific conclusions are:

1. Give great care and attention to the details of the monitoring installation. This begins with the planning stage. Give details down to the tiniest minutia, to any subcontractors who are involved in installing cabling and equipment, and be on hand as much as possible to supervise. The subcontractors for Linford did an excellent job, but detailed liason was still necessary. The scope for creating problems because of careless installation is enormous and potentially very expensive.

2. If possible, be generous with sensors and data logging capacity - plan for redundancy, as some are bound to go wrong.

3. Parallel wiring as used at Linford is probably out-of-date given the advances made in digital technology, and in particular, micro-computer based logging systems. However, doubtless there will be equally as many things to go wrong with these systems too.

4. Do not underestimate the amount of time and effort involved in commissioning monitoring equipment. Make estimates and then double them.

5. Plan for as much technician back-up as possible, of the best possible quality. The Linford project enjoyed the part-time services of one very experienced senior technician, and one full-time, relatively inexperienced technician for half the project duration. For substantial amounts of time, this could easily have been doubled and the individuals would still have been stretched. Unfortunately, the pattern of technical activity on field trials is very uneven - large efforts are required during installation and commissioning, a lesser (but constant) amount is required during the monitoring periods, for regular equipment maintenance, followed by relatively little activity during data analysis. Finally, a relatively short, but intense effort is required at the end of the project, for decommissioning purposes.

6. Do not underestimate the sheer volume of data that will be collected, and the problems that will arise in handling, storing and analysing huge quantities of data.

7. Allow ample time for cleaning the data. This is a very tedious, but essential task. Depending on the size of the project, this can take several months and places considerable strain on the researchers involved.

8. Make sure that the computer and operating system to be used are capable of handling the data and supporting the range of analysis required. Allow for possible major changes in computer hardware and software during the lifetime of the project.

9. Do not underestimate the amount of time required to write the software for handling the data, cleaning it, entering it into a database, extracting it and carrying out analysis. This is a major task, involving months of difficult work if there are no existing programs that can suitably be adapted.

10. Fast and simple graphical presentation of raw data is very important, as this paves the way to efficient and productive analysis.

11. Try to anticipate as much as possible the kind of analysis that will be carried out. This is down to good experimental design. However, it is inevitable that at some stage the researchers will find themselves in the confusing and frustrating position of not really knowing what to do with the data once it is collected. It is all too easy to lose sight of the project objectives or become sidetracked. Though the researchers may consider themselves "experts", it is easy to underestimate one's own ignorance.

12. The combination of a test house, where controlled experiments can be carried out, and real, occupied houses of the same type was very successful in this project.

13. It is adviseable to collect as much back-up data as possible, by means other than the main monitoring system. For Linford this consisted of manual gas and electricity readings (which were extremely useful as a check against summation of the hourly data), continuous outside air temperature recordings using a thermograph, maximum and minimum outside air temperatures, weather conditions (visual description) and observations of the window blinds and curtains in the occupied houses.

Manual gas and electricity readings on a weekly or fortnightly basis should be regarded as essential.

14. Maintain good relations with the occupants of monitored houses. This means adopting a low profile, being sensitive and sympathetic towards their right to privacy in their own homes, while making oneself available for casual conversations about their houses and the progress of the project, occasionally lending a hand to solve problems with for example, the heating system.

15. A good deal of enthusiasm is required over long periods of time. Field trials can be very frustrating, but ultimately rewarding experiences. They are not cheap, however.